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A PETROGRAPHIC AND GEOCHEMICAL STUDY OF THE
NISKU FORMATION IN THE LEDUC - WOODBEND FIELD, ALBERTA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

by

GUY MICHEL LAFON, Ingenieur Civil des Mines

EDMONTON, ALBERTA

September, 1965

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "A Petrographic and Geochemical Study of the Nisku Formation in the Leduc-Woodbend Field, Alberta", submitted by Guy Michel Lafon, Ingenieur Civil des Mines, in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

A petrologic and geochemical study was made on three sections of the Upper Devonian Nisku Formation in the Leduc-Woodbend oilfield, central Alberta, Canada. The investigation was directed toward determining the depositional pattern of these dolomitized limestones, collecting ecological data on Upper Devonian fossils, and examining the possible usefulness of geochemical analysis of dolomitized carbonate units. The methods used included macroscopic observation of the cores, petrographic study of thin sections, X-ray diffraction analysis of the clay fraction, and the establishment of chemical and mineral profiles by X-ray fluorescence analysis.

Three submembers and fourteen petrographic facies were recognized: the lower Nisku represents rather shallow, quiet conditions, favourable to the development of tabular stromatoporoids associated with dasycladacean algae; the middle and upper Nisku were still shallower and more turbulent, favouring the growth of Amphipora and of encrusting algae; the upper Nisku is characterized by an increase in terrigenous silt content announcing a more restricted environment.

The chemical study permitted the differentiation of the rock types with a relatively high detrital content; non-argillaceous petrographic facies could not in general be characterized by specific chemical characteristics.

The dolomitization of the Nisku Formation took place in two successive phases: a volume for volume transformation which generally preserved the gross texture of the rock, and probably took place before the end of the Devonian, was followed at an unknown date by the action of magnesium-bearing solutions which altered the consolidated rock around the permeability channels.

Anhydrite, which constitutes up to 15 percent of the rock in places, has a mixed void-filling and replacement origin.

ACKNOWLEDGEMENTS

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Thanks are extended to Imperial Oil Enterprises Ltd., which provided generous access to their cores, records and core storage facilities in Edmonton.

Mr. Frank Dimitrov did the drafting and the photographic work. Mrs. Elizabeth Vincze prepared the thin sections and Miss Mae Patterson typed the manuscript and the final copy.

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INTRODUCTION

This work is a petrologic and geochemical study of three sections of the Nisku Formation in the type area, the Leduc-Woodbend oilfield. The wells studied were the following:

Imperial Leduc 200, located in 16-18-50-26 W 4th Meridian

Imperial Leduc 177, located in 12-2-50-26 W 4th Meridian

Futurity Weisener 1, located in 2-17-49-25 W 4th Meridian

The general location of the oilfield and the positions of the three wells used are shown in Figures 1 and 2. It was decided to choose wells along a north-west southeast cross-section through the oilfield, which would permit observations of the gradation from less to more restricted depositional conditions.

The objectives of the study were as follows:

To reconstruct as much as possible of the depositional pattern of a dolomitized limestone by investigation of relict textures.

To collect more data concerning the ecology of upper Devonian fossils.

To test the possibilities of geochemical analysis in the differentiation of contrasting sedimentary facies in a dolomitized carbonate unit.

The methods employed for the study were: Visual observation of the cores with a binocular microscope, which, as shown by Klován (1963), allows a good estimate of the actual composition of the bulk rock; the study of thin sections with the petrographic microscope; the study of the clay minerals by X-ray diffraction methods; and the establishment of chemical and mineral profiles with the aid of X-ray fluorescence analysis.

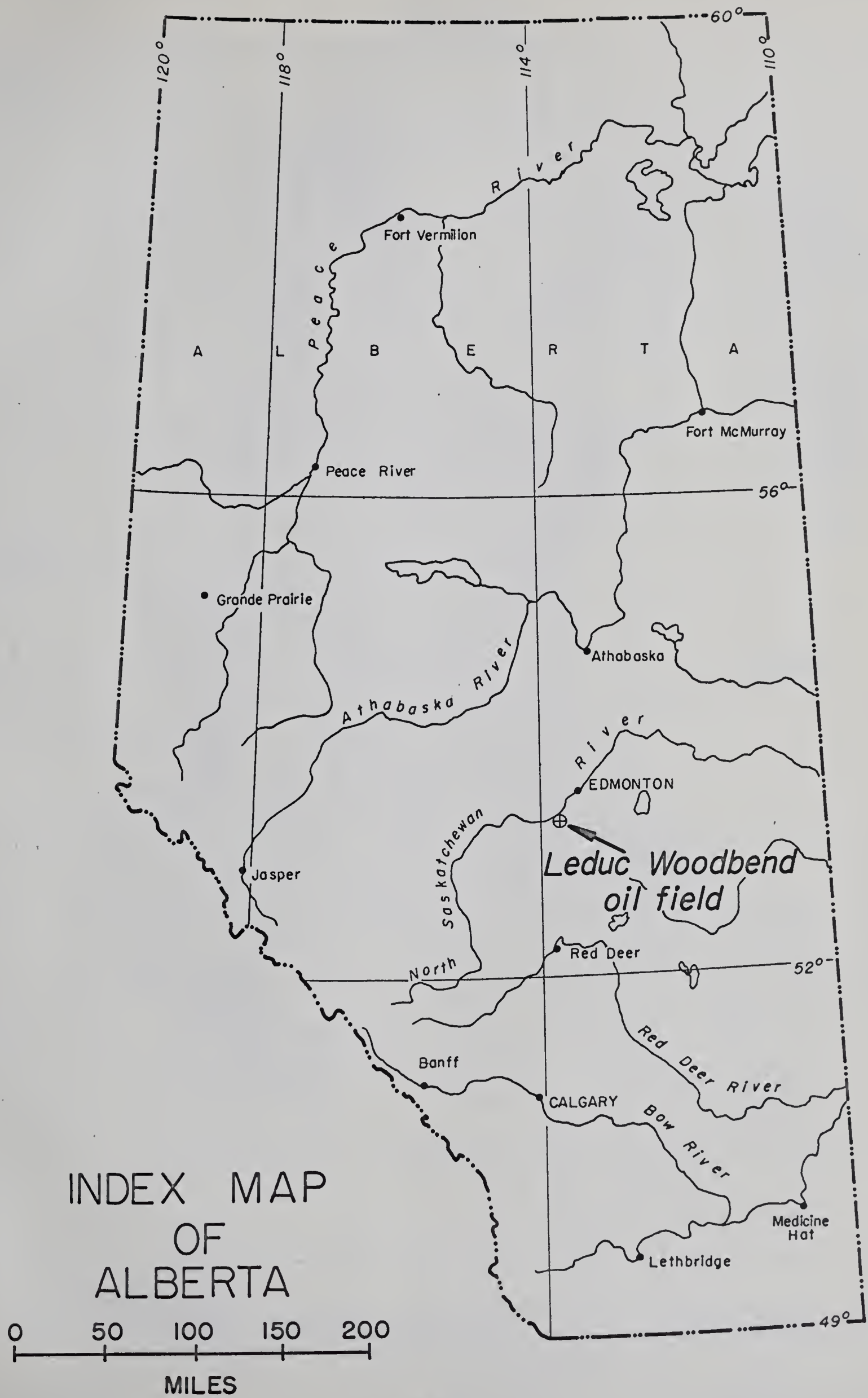


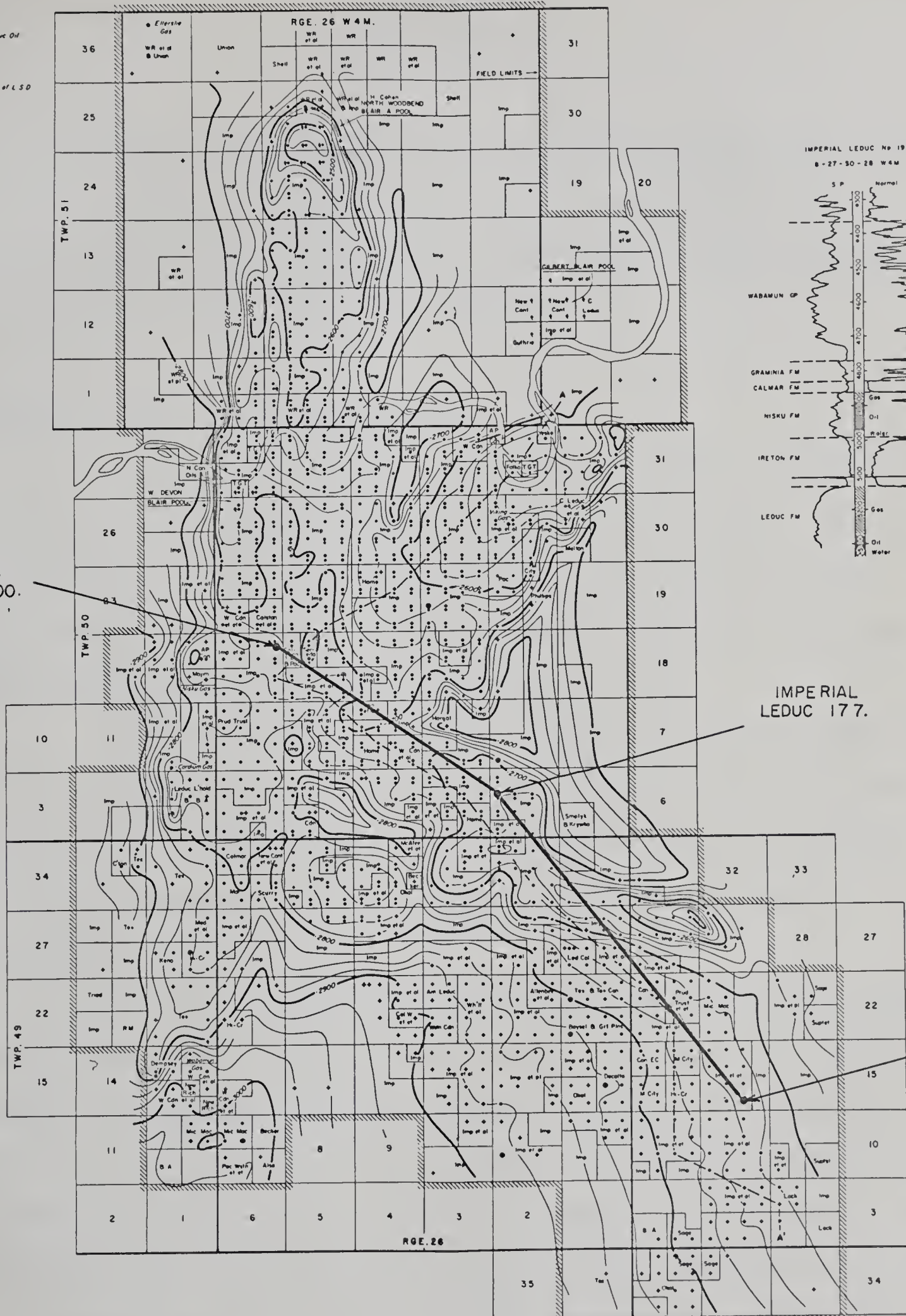
Figure 1.

LEDUC FIELD 25' CONTOURS - NISKU FM.

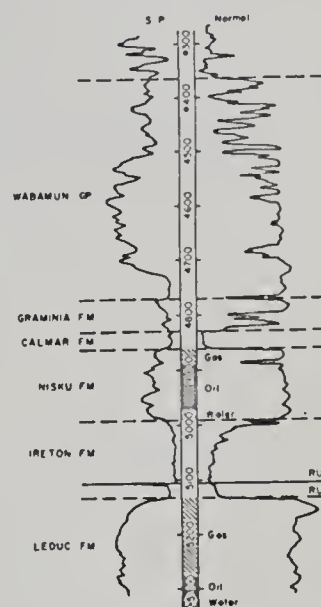
0 1 2 MILES

LEGEND
• Ellerslie Gas
• Durr Nisku - Leduc Oil
• Leduc Oil
• Ellerslie Oil

NOTE
All wells plotted in centre of L.S.D.

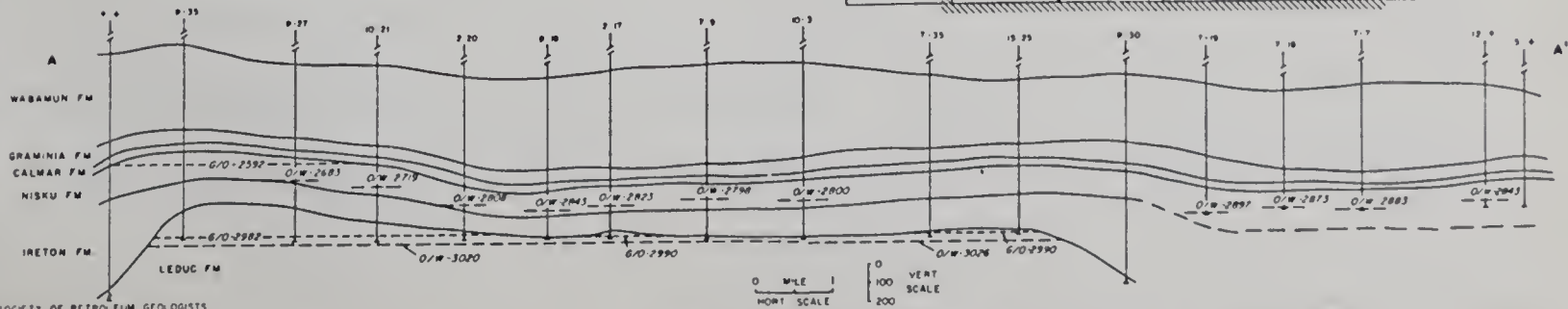


IMPERIAL LEDUC No 198
8-27-50-28 W 4 M



IMPERIAL
LEDUC 177.

FUTURITY
WEISNER
1.



STRATIGRAPHY

Devonian strata are among the most widespread sediments in western Canada. Since the discovery of oil in Devonian carbonates of central Alberta in 1947, a detailed picture of Devonian stratigraphy in western Canada has been worked out. The generalized nomenclature is shown in Figure 3.

UPPER DEVONIAN IN CENTRAL ALBERTA

The Upper Devonian strata in central Alberta consist of, in ascending order: the Beaverhill Lake Formation, the Woodbend Group, the Winterburn Group, and the Wabamun Group. First defined as formations, these units were raised to group status by Belyea (1955). Following is a summary of the historical evolution of the Edmonton area during Woodbend and Winterburn times.

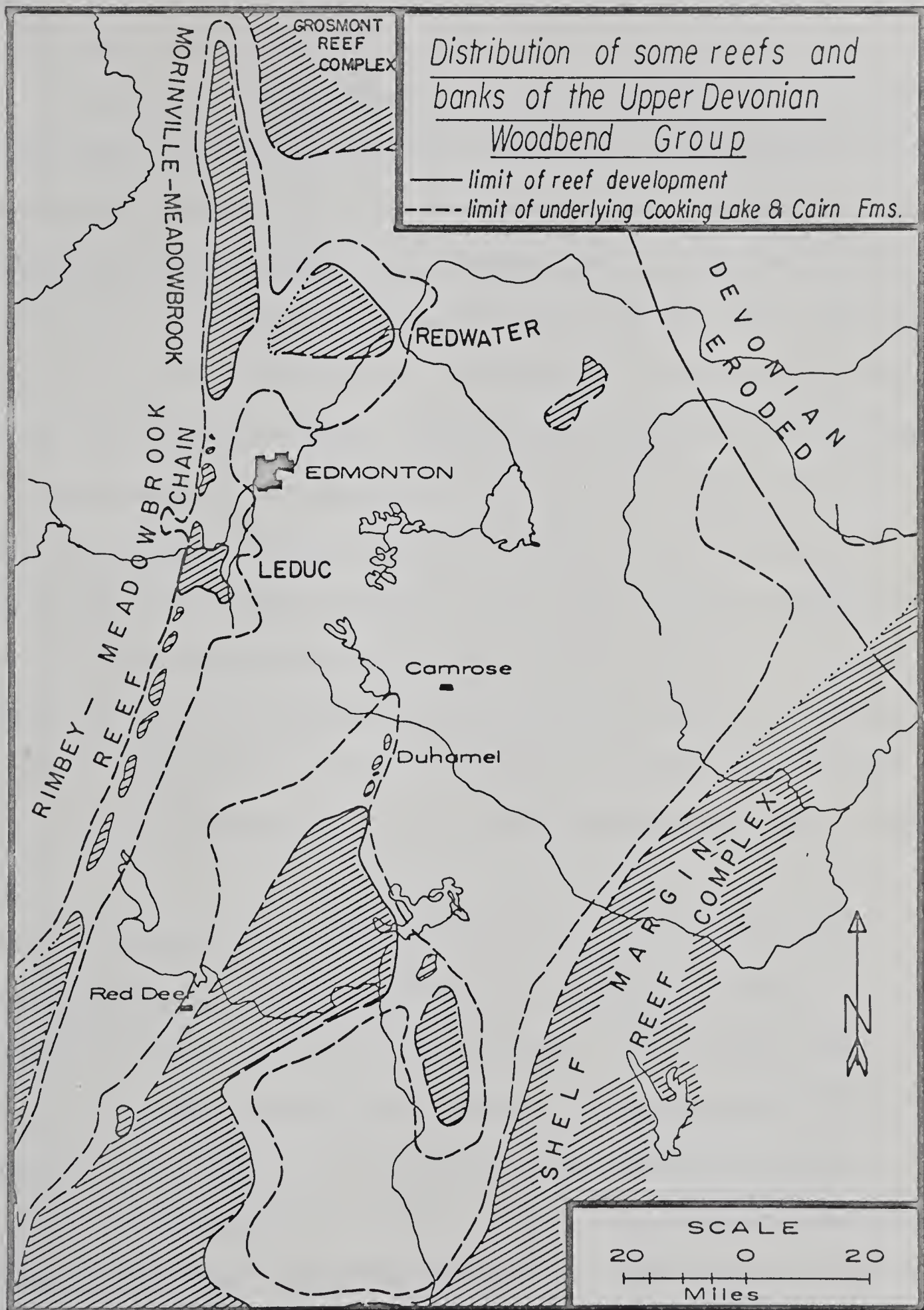
At the start of Woodbend deposition, the Alberta basin became differentiated into a shale basin in the west and a broad carbonate shelf to the east. To the east of the Rimbey-Meadowbrook reef trend, shelf deposition took place building the Cooking Lake Formation in central and northeastern Alberta to a thickness of approximately 200 feet.

The carbonates of the Cooking Lake Formation are of several types grading laterally and vertically into one another: Stromatoporoid-amphiporoid calcarenites; amphiporoid limemuds; calcarenites containing stromatoporoids and algae, scattered and rolled by wave or current action; calcilutites to calcarenites, containing a few shredded organic debris and abundant pellets, cemented in places with sparry calcite; very fine grained rocks (less than 10 microns in grain size) grading to fine calcilutites and containing ostracod and gastropod shells as well as some other skeletal debris. Cooking Lake sediments are well bedded and occur often as rhythmic alternations. Beds range from less than one foot to ten feet in thickness; stromatoporoid mounds

SERIES	STAGE	DISTRICT OF MACKENZIE NORTHEAST BRITISH COLUMBIA NORTHERN ALBERTA	ROCKY MOUNTAINS AND FOOTHILLS	ALBERTA PLAINS			SASKATCHEWAN MANITOBA	MONTANA NORTH DAKOTA	MAP UNITS This paper
UPPER DEVONIAN	FRASNIAN	KOTCHO FORMATION TETCHO FM. TROUT RIVER KAKISA FM. REDKNIFE FM. JEAN MARIE MBR. FORT SIMPSON FM.	PALLISER FORMATION U. ALEXO ARCS MBR. GROTTO MOUNT HAWK FM. PEECHEE SOUTHESK FORMATION CAIRN FORMATION FLUME MBR. FLUME FM.	SOUTHERN WABAMUN GP. BIG VALLEY STETTTLER CROWFOOT FORMATION WABAMUN GP. STETTTLER GRAMINIA FM. CALMAR FM. NISKU FORMATION SOUTHESK FM. GROTTO MEMBER PEECHEE MEMBER CAIRN FORMATION	CENTRAL WABAMUN GP. BIG VALLEY STETTTLER GRAMINIA FM. CALMAR FM. NISKU FORMATION CAMROSE IRETON FORMATION LEDFORD FM. COOKING LAKE FM. MAJ-EAU LAKE MBR.	NORTHEASTERN WABAMUN GROUP GRAMINIA FORMATION CALMAR FM. NISKU FORMATION IRETON FORMATION HONDO FM. GROSMONT FORMATION COOKING LAKE FM.	THREE FORKS FM. BIG VALLEY MBR. STETTTLER MEMBER THREE FORKS FM. BIRDBEAR FORMATION BIRDBEAR FORMATION DUPEROW FORMATION SOURIS RIVER FORMATION	THREE FORKS FM. POTLATCH MBR. THREE FORKS FM. BIRDBEAR FORMATION DUPEROW FORMATION SOURIS RIVER FORMATION	PALLISER-WABAMUN THREE FORKS UPPER CARBONATE LOWER CARBONATE DUPEROW - IRETON BEAVERHILL LAKE

Table of Upper Devonian formations. (after Belyea, 1964)

FIG. 3.



(after Belyea, 1960)

Figure 4.

commonly reach a thickness of 25 feet, and, where they build up at the expense of shales, may reach 150 feet.

At the end of Cooking Lake time, carbonate deposition related to organic activity became localized on parts of the Cooking Lake shoals (Andrichuk, 1958a). Vertical growth of these reefs, known as the Leduc Formation, probably was the consequence of a rapid increase in the subsidence rate. The reefs are of various shapes, but most are elongate in the direction of the chain they build. Their upper surfaces are irregular, and it is not known whether this is the result of original deposition or of subsequent erosion. Extensive dolomitization has obliterated most of the original depositional features, so that little evidence remains as to the genesis of these bodies. Only the Redwater, Golden Spike, Willingdon, and Duhamel reservoirs and a few occurrences in the mountains remain undolomitized and can provide the data necessary for a better insight into the actual structures of the Alberta reefs. The Redwater reef was investigated by Andrichuk (1958a) and later by Klován (1963). Their studies showed that the Devonian reefs more closely resemble the West Indian type rather than the Pacific type of present day reefs.

The carbonates of the Woodbend Group grade laterally into shales. East of the Rimbey-Meadowbrook reef chain, the Cooking Lake Formation is overlain by the Duvernay Formation. A type section, 175 feet thick, was designated in the Duvernay area, east of Edmonton, by the Geological Staff of Imperial Oil Ltd. (1950). It consists of grey to brown fossiliferous limestone, sometimes with black argillaceous partings, greyish brown argillaceous limestone, and dark grey and black to brown calcareous shale. From the type section, the Duvernay thins southward and thickens north and northeastward. Its lithology is highly variable from place to place.

West of the Rimbey-Meadowbrook reef chain, the Duvernay Formation

represents the base of the Woodbend Group and lies directly on the Middle Devonian Beaverhill Lake Formation. There, the Duvernay consists of "a thin, black shale at the base followed upward by greenish grey, fissile shales carrying poorly preserved scaphopods and pteropods, overlain by a sequence of grey and black shales and limestones that grade upwards into black shale and black to brown silty shales and siltstones. The basal black shale and the greenish grey shales are the stratigraphic equivalent of the carbonates that form the Cooking Lake Formation of central Alberta". (Belyea, 1964). The Duvernay shale section thins as the Cooking Lake carbonates thicken approaching the reefs.

The Duvernay is overlain by a formation consisting mainly of greenish grey shales known as the Ireton Formation in central Alberta. Its thickness varies from a few feet to several hundred feet, depending upon the amount of underlying carbonate buildup. There is a general increase in thickness from south to north, and the Ireton passes gradually northward into the undifferentiated Fort Simpson Shale.

In central Alberta, the Ireton may be divided into three members (McCrossan, 1961). The lower member is a poorly fossiliferous, argillaceous calcilutite. The middle member is a monotonous sequence of greenish grey calcareous shale, with very little limestone. The upper member consists of interbedded limestones and shales, locally dolomitic toward the top. It is a transition zone between the underlying shale and the overlying carbonates. In the vicinity of the reef chain, the lower and middle Ireton members have a combined thickness of about 450 feet.

Woodbend time was followed by the deposition of the Winterburn Group, comprising in ascending order the Nisku, Calmar, and Graminia Formations. A type section was designated for the Winterburn Group, then called Winterburn Formation, by the Geological Staff of Imperial Oil Ltd. (1950).

It occurs in the British American Pyrcz No. 1 well, located in Lsd. 12, Sec. 25, Tp. 50, R. 26, W. 4 M. Total thickness of the Winterburn at the type section is 250 feet.

Overlying the Ireton, the Nisku Formation is a relatively uniform dolomite unit varying in thickness from 135 to 170 feet. Belyea (1955) subdivided the Nisku into three informal members:

- the lowermost or A member is a grey and buff, finely crystalline dolomite similar to the uppermost reef-like Ireton.
- the middle or B member is "a crystalline dolomite with an apparently irregular distribution of original porosity that suggests vuggy reef growth and fine-grained inter-reef dolomite, rather than a simple biostrome".
- the upper or C member consists of interbedded dolomites and siltstones and seems to be gradational laterally and vertically into the Calmar Formation. The C member is sharply separated from the underlying B member by a thin bed of sandstone and bright green shale.

Due to the differential compaction of the Ireton shales, the Nisku Formation, in the Leduc Woodbend field, drapes above the carbonate build-ups of the Leduc, paralleling their topography in an attenuated fashion.

The Calmar Formation is 44 feet thick in the type section, where it consists of light green shale and argillaceous siltstone with some red mottling. Throughout most of the Leduc-Woodbend oil field, its colour is greenish grey, and it is characterized by its quartz silt content. The Calmar is well developed in the Leduc area and westward but thins rapidly to the north and the south of the type section. Its relatively high radioactivity helps to differentiate it from the overlying Graminia.

The Graminia Formation, 50 feet thick at the type section, consists of white, quartzose, fine-grained sandstones and siltstones, and interbedded

buff, crystalline, silty dolomites with variable porosity. East and southeast of the type area, the dolomites grade into anhydrite and the formation thins.

PETROGRAPHY

CLASSIFICATION OF CARBONATE ROCKS

General Statement

In recent years, carbonate petrography has been extensively developed as a result of an increased awareness of the economic significance of carbonate rocks as oil reservoirs. The need of a detailed and precise classification of these rocks has been acutely felt by most workers and there is an almost unanimous feeling that such a classification should be based on the nature and the size of the textural components.

The classification used in this report is the one proposed by Leighton and Pendexter (1962). This classification, as true of most of the classifications now available, deals primarily with limestones, and interprets dolomites in the light of the proposed limestone rock types. However, the writer feels that the Nisku dolomites have retained enough of their original textures to be practically classified according to Leighton and Pendexter's scheme.

Textural Components of Limestone

Most limestones can be characterized by the types and relative amounts of the following components: grains, lime mud, cement, pore space, organic structures, and recrystallized calcite.

Grains are discrete particles capable of forming a rock framework. They are the equivalent of sand in sandstones or silt in silstones. Their upper size limit is fixed at 2 mm, the boundary between sand and gravel in Wentworth's scale. The lower size limit adopted in this report, 3.9 microns, is determined by the impossibility of correctly identifying grains of a smaller size with the petrographic microscope. It corresponds to the break between silt and clay in

Wentworth's scale and was advocated by Folk (1962). Leighton and Pendexter recognize five grain categories: detrital grains, skeletal grains, pellets, lumps, and coated grains.

Lime mud, or micrite, is roughly the size equivalent of the argillaceous material in a dirty sandstone or in a mudstone. It refers to lime ooze of either mechanical or chemical origin and is given an arbitrary upper size limit of 3.9 microns.

Cement is a clear crystalline component that has been precipitated in the spaces between the grains.

Pore space is the remaining open space between grains, and depends upon the roundness, shape, size, sorting and packing of the original grains as well as upon secondary processes.

Organic structures are the products of colonial frame builders such as corals, bryozoa, algae, stromatoporoids, and so on, which make up the bulk of certain limestones; more commonly, however, the limestones that contain such organisms are a complex mixture of in situ builders and of mechanically deposited grains and lime mud.

Recrystallized calcite constitutes patchy mosaics that have resulted from recrystallization of smaller calcite particles. Cement is excluded from the definition.

Figure 5 gives a graphic presentation of the classification used and lists the different kinds of limestones that may be distinguished by the use of grain to micrite ratios. The ratios used can be changed to suit the specific needs of a particular study.

Dolomites

Dolomites are, by definition, carbonate rocks composed of more than

TEXTURAL CLASSIFICATION OF LIMESTONES

GRAIN /MICRITE RATIO (a)	% GRAINS(b)	GRAIN TYPE(c)						Organic Frame- Builders	No Organic Frame- Builders
		Detrital Grains	Skeletal Grains	Pellets	Lumps	Coated Grains			
9 : 1	~ 90 %	Detrital Ls.	Skeletal Ls.	Pellet Ls.	Lump Ls.	Oolitic Ls. Pisolithic Ls. Algal encr.Ls.	Coralline Ls. Algal Ls. Etc.	Caliche Travertine Tufa	
1 : 1	~ 50 %	Detrital- Micritic, Ls.	Skeletal - Micritic Ls.	Pellet - Micritic Ls.	Lump - Micritic Ls.	Oolitic - (Pisolithic-Etc.) Micritic Ls.	Coralline- Micritic Ls. Algal- Micritic Ls. Etc.		
1 : 9	~ 10 %	Micritic- Detrital Ls.	Micritic - Skeletal Ls.	Micritic- Pellet Ls.	Micritic - Lump Ls.	Micritic - Oolitic (Pisolithic Etc.) Ls.	Micritic- Coralline Ls. Micritic- Algal Ls. Etc.		
		Micritic				Limestone			

(after Leighton and Pendexter, 1962)

FIG. 5.

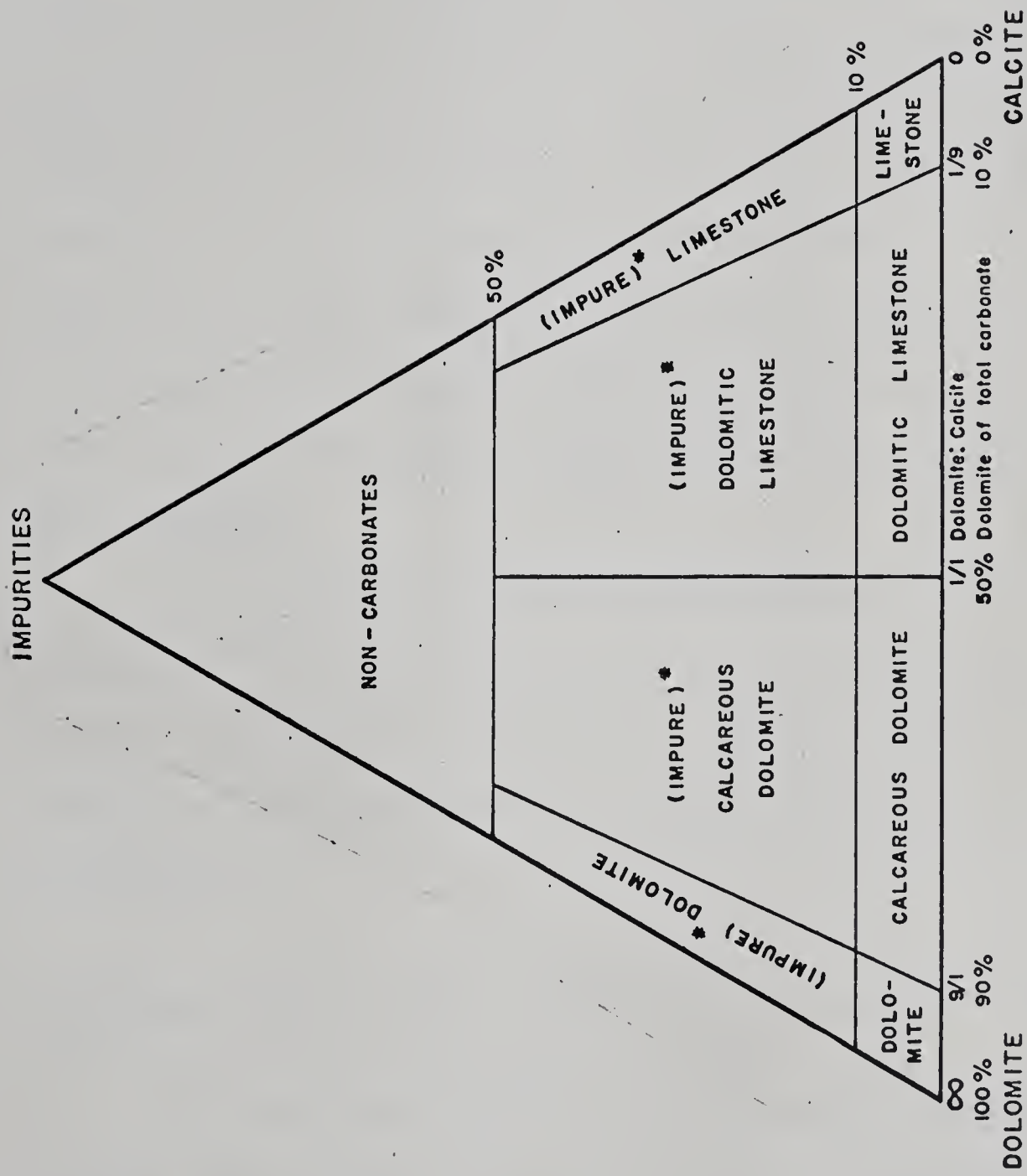


FIG. 6. Compositional terminology of carbonate rocks (after Leighton and Pendexter, 1962)

50 percent, by weight, of the mineral dolomite. Figure 6 represents the compositional range of a carbonate rock. The system here adopted for naming dolomites is based primarily on a compositional grouping modified by appropriate textural terms.

Leighton and Pendexter recognized the division advocated by Cayeux (1935): calcareous dolomites, containing 50 to 90 percent, by weight, of the mineral dolomite; and dolomites, containing more than 90 percent of the mineral dolomite. The names "dolomite" and "calcareous dolomite" are followed, in parentheses, by the terms describing the limestone grains and textures that remain as calcite or that, although dolomitized, still are recognizable. When a relict limestone structure is still identifiable, the name dolomite is followed, in parentheses, by the textural name of the limestone with the prefix "dolomitized"; for instance, dolomite (dolomitized colitic limestone).

In naming dolomite types, it is often useful to add as modifiers, either before or after the name, descriptive terms such as: saccharoidal, laminated, breccia, mosaic textured, microcrystalline, and so on. Table 1 shows the nomenclature adopted to describe the size of the dolomite crystals and of the detrital material.

DESCRIPTION OF THE NISKU FORMATION CONSTITUENTS

The constituents of the Nisku Formation may be grouped under three main headings: organic megastructures (dolomitized skeletons of organisms that are larger than 2 mm; crystalline dolomite groundmass (the whole of the dolomitized grains, cement and mud); other constituents. In the following discussion, the term "recrystallized" will apply only to those dolomite crystals that have resulted from the alteration of a group of smaller dolomite crystals.

Organic megastructures

They comprise essentially: stromatoporoids, algae, corals, and shells.

Stromatoporoids

Sections of stromatoporoids, when well preserved, show a complex grid-like pattern which permits their identification (Galloway, 1957). In the Nisku Formation, dolomitization has generally obliterated these microscopic features, which makes precise identification practically impossible; they are therefore distinguished by their external shapes. The main types observed may be classified as tabular, dendroid, and massive.

Tabular stromatoporoids - According to Klován (1963), tabular types range in thickness from 2 mm to 10 cm but in the Nisku Formation, no thicknesses greater than 5 cm were observed. Growth habits are variable. The very thin types, pancake shaped, are common but seldom develop an anastomosing skeleton as in Euryamphipora Klován.

The calcite skeleton of the tabular stromatoporoids has been altered to dolomite crystals which are 20 to 70 microns in the greatest diameter, anhedral, angular to subangular and tightly interlocking. The dolomitized tissue (tissue is here taken in the sense of Galloway, meaning "the microscopic structure or histology of the laminae, the pillars, the cysts, or other finer structure"), is cream white to light brown in reflected light, but appears heavily pigmented with brown organic matter when studied in thin section. The canal and pillar structures are generally obliterated by dolomitization; in one instance however, canals and parts of the tissue were preserved, which permitted the identification of *Stromatopora*? sp. (Plate I, Fig. 1). In some cases, the canals and most of the surrounding tissue have been replaced by clear transparent dolomite crystals, oriented so as to have their optical axes parallel; consequently, they all show high or low relief for a given position of rotation of the microscope stage, con-

TABLE 1

GRAIN AND CRYSTAL SIZE NOMENCLATURE			
SIZE		NOMENCLATURE	
Millimeters	Microns	Mechanical texture	Crystalline texture
— 64 —		very coarse pebble	extremely coarse crystalline
— 16 —		coarse pebble	
— 4 —		medium pebble	
— 2 —		fine pebble	
— 1 —	— 1000 —	very coarse sand	very coarse crys- talline
— 1/2 —	— 500 —	coarse sand	coarse crystalline
— 1/4 —	— 250 —	medium sand	medium crystalline
— 1/8 —	— 125 —	fine sand	fine crystalline
— 1/16 —	— 62 —	very fine sand	very fine crystalline
— 1/32 —	— 31 —	coarse silt	coarse microcrys- talline
— 1/64 —	— 15.6 —	medium silt	medium microcrys- talline
— 1/128 —	— 7.8 —	fine silt	fine microcrys- talline
— 1/256 —	— 3.9 —	very fine silt	very fine micro- crystalline
		ooze	aphanocrystalline

trasting sharply with the randomly oriented crystals that build the rest of the skeleton. When viewed in the position of maximum relief contrast, the oriented crystals exhibit a comb-like pattern that may be related to the original canal structure (Plate I, Fig. 2).

Recrystallized patches consist of dolomite crystals which are 150 to 300 microns in the greatest diameter and anhedral to subhedral. Fractures and fissures, probably formed by load action, are filled with clear transparent dolomite which is very similar to the canal fillings, but sometimes shows anhedral amoeboid crystals. It seems probable that these clear dolomite replacements were effected preferentially in the zones of greatest original porosity.

Although dolomitization and, later, recrystallization have destroyed most of the microscopic structure, the laminar appearance of the thick tabular stromatoporoids (one centimeter and thicker) is conspicuous, particularly in polished sections. The writer believes that this represents the original latilaminae of the nondolomitized stromatoporoids.

Dendroid stromatoporoids - These belong to the Family Idiostromatidae as defined by Galloway (1957). Two genera are important in the Nisku Formation, Amphipora and Stachyodes.

Amphipora is one of the most abundant organisms in the Nisku. It is constituted by slender, vermicular stems that branch at long intervals, with a large, variable axial tube and large vesicles near the surface. Overall diameter of a stem is 1 to 5 mm, and the longest stems observed are about 6 cm, for the observation was limited by the width of the slabs studied. Attached stems were not seen and branching stems are indeed rare.

Observed specimens of Amphipora are made up of dolomite crystals, 20 to 70 microns in the greatest diameter, mostly anhedral but sometimes showing subhedral faces, angular and tightly interlocking (Plate I, Fig. 3). In the upper

and middle Nisku, these crystals are lightly pigmented with brown organic matter and, when surrounded by a heavily pigmented groundmass, appear lighter in colour than the rest of the rock; when, on the contrary, they are surrounded by transparent dolomite, they appear darker. In the lower Nisku, where Amphipora is associated with tabular stromatoporoids, the constituent crystals are as heavily pigmented as those of the latter, that is, much darker than usual.

The central canals have played a variable role. They are sometimes filled with transparent dolomite crystals, sometimes only partly occupied by dolomite rhombs. When leaching has been important, they are enlarged and exhibit jagged contours.

The tissue structure has generally been destroyed by dolomitization, and the great majority show a structureless isotropic arrangement of the dolomite crystals. In a few instances however, it is still possible to observe an obscure system of large vesicles near the surface of the stem (Plate III, Fig. 6).

Recrystallization of the dolomitized Amphipora skeletons is not common. Recrystallized patches show dolomite crystals that are 150 to 300 microns in diameter, anhedral to subhedral and generally transparent. They are encountered near the canals or near the surface.

Stachyodes has a dendroid coenosteum, with a tabulate axial tube. It was not often encountered and the specimens observed were always fragmental, thus the lengths of the stems and the mode of attachment could not be determined. According to Klován (1963) Stachyodes probably grew as bush-like colonies in a manner similar to present day corals. Their microscopic features have been destroyed by dolomitization, and the only remaining tissue structure is an arrangement of concentric rows of dolomite crystals, 20 to 150 microns in size, anhedral, angular, and tightly interlocking. The crystals are as heavily pigmented

with brown organic matter as those of the neighbouring tabular stromatoporoids.

Stachyodes may be identified by some other diagnostic features: the rapid and important variations in the outer diameter of the stems (3 mm to 2.5 cm according to Klován) and the absence of vesicles near the surface.

Massive stromatoporoids - These are extremely rare and exhibit sub-spherical, nodular and dome-like forms (Plate I, Fig. 4). Dolomitization and recrystallization have destroyed all trace of microscopic structure in the three occurrences that were observed. However, the shape of the skeleton was easily identifiable because of a sharp colour contrast. The texture of these altered fossils is similar to the recrystallized patches observed in other types of stromatoporoids.

Algae

Modern algae effect carbonate deposition in three different ways. The red algae precipitate calcium carbonate as a skeleton and thus contribute skeletal grains to sedimentation. A second mode is exemplified by the blue-green algae, which are able to trap fine sediments with their mucilaginous filaments. A third manner is shown by many green algae, which secrete fine aragonite needles in their thalli, contributing in this way to calcareous mud deposition after death.

In the Nisku Formation, it was not possible to identify any microscopic structure of certain algal origin. The structures referred to as algal are irregularly shaped patches that contrast by their colour, their crystal size, and their horizontal banding with the surrounding rock. The determination made is tentative and the writer has relief for identification on illustrations displayed by Kirmani (1962).

These structures in the Nisku are made up of more or less horizontal

bands of microcrystalline dolomite. The crystals are 20 to 100 microns in the largest diameter, anhedral, subangular to very angular, tightly interlocking and rather heavily pigmented with brown organic matter (Plate I, Fig. 5). They have trapped a small amount of quartz silt (less than one percent) which is of the same size as the surrounding dolomite crystals and subangular to very angular, some exhibiting jagged edges. Quartz silt grains found in the dolomite groundmass that surrounds the algal structures have the same characteristics.

Macroscopically, the algal structures are horizontal dark bands separated by lighter dolomite (Plate I, Fig. 6). The bands are slightly undulating and have wavy boundaries. They are often ruptured and displaced vertically by what seems to have been load action.

These structures are tentatively interpreted as the result of the activity of blue-green algae.

Associated with Amphipora and tabular stromatoporoids, tubular and bag-like skeletons occur in the lowest part of the Nisku Formation. The tubular ones are 0.5 to 1.5 mm in diameter, with walls 200 to 400 microns thick, constituted by concentric and elongate dolomite crystalline fibers (Plate I, Fig. 7). With nicols crossed, these skeletons show a characteristic cross-shaped extinction.

These features resemble those established by Choubert (cf. Johnson and Konishi, 1958) in the definition of Robertia, an alga from the Family Dasycladaceae. However, no concentric canal or openings could be observed, making this identification very tentative.

The bag-like skeletons show triangular sections and are structureless. They resemble another dasycladacean genus, Catena Maslov. As with the preceding organisms, this is only a tentative identification.

Stromatoporoid-algal consortium

This is an encrusting fossil structure found associated with tabular stromatoporoids. It consists of alternating layers 1 to 3 mm thick. Layers that are light in colour in reflected light have a structure analogous to that of the dolomitized stromatoporoids; the dark layers are composed of crystalline dolomite groundmass. This fossil seems to be similar to the one described by Klovan under this name and appears to have been formed by an intimate association of stromatoporoids and blue-green algae.

The volumetric importance of the stromatoporoid-algal consortium is negligible.

Corals

No colonial corals were observed during the study. A few solitary horn-shaped corals are associated with the tabular stromatoporoids. The septa and the walls are usually recrystallized so that precise identification is impossible. Most of the corals observed belonged to the Order Rugosa.

Thamnopora, a tabulate coral, was observed in a few instances associated with a variety of skeletal debris. Under this name have probably been included the genus *Coenites* and bryozoans, since the recrystallization of the walls makes identification difficult.

Thamnopora is described by Hill and Stumm (1956) as "massive, tuberoso or ramose; walls thickened, increasing distally; septal spines poorly developed, mural pores numerous, tabulae thin". In the Nisku Formation, only broken stalks could be observed, so that the mode of attachment and the growth habit are unknown. Individual stalks range from 3 mm to more than 20 mm in diameter. In axial sections, they are variously shaped, but are mostly finger-like. The walls of specimens of Thamnopora ? sp. found in the Futurity Weisener I well

are made up of dolomite crystals, 20 to 50 microns across, angular to subangular, anhedral to subhedral, tightly interlocking and heavily pigmented with brown organic matter (Plate I, Fig. 8). The thecal cavities are usually still open with dolomite rhombs growing toward the centre.

Brachiopod and Pelecypod shells

These are encountered in the lower part of the Nisku Formation. Recrystallization makes their identification probably impossible, unless a whole shell is observed. In one instance, it was still possible to observe the two layers of a brachiopod shell; they had been altered to dolomite crystals, subhedral, 300 to 500 microns in size, which were still arranged in two superposed rows (Plate II, Fig. 1). This pattern changed gradationally in another part of the same shell to a structureless aggregate of smaller (50 to 200 microns) dolomite crystals arranged in a random pattern.

Pelecypod shells are composed of a structureless arrangement of small dolomite crystals, similar to the ones described above (Plate II, Fig. 2). It is impossible to differentiate between brachiopods and pelecypods in fragments of shells when the layered structure has been destroyed.

Crystalline dolomite groundmass

Under this heading are grouped the constituents less than 2 mm in the largest diameter. As enumerated in the discussion of classification of carbonate rocks, they comprise grains, dolomitized lime mud, cement, and recrystallized dolomite. They will be dealt with in two successive parts: the first includes the elements which the writer has reasons to consider as being not recrystallized, and whose identification is therefore more accurate; the other deals with the recrystallized constituents and a tentative attempt is made to retrace them to

the original material.

Unrecrystallized constituents

Unrecrystallized constituents are found generally in laminated dolomite or shaly dolomite. In the Imperial Leduc 177 well, unrecrystallized but dolomitized calcarenites are present.

In one occurrence of laminated dolomite (Plate II, Fig. 3) two types of grains contrast sharply: (a) small crystals, 5 to 30 microns in the greatest diameter, anhedral, angular to subangular, tightly interlocking, are coloured a reddish brown in transmitted light by a small amount of argillaceous matter; this colour often becomes a greenish grey when viewed in reflected light; the probable original material was an argillaceous calcilutite or lime mud. (b) coarser crystals, 20 to 100 microns in size, anhedral, angular, tightly interlocking, lightly pigmented, and mosaic-textured, separate the laminae described above; they may be derived partly from Amphipora fragments, partly from brachiopod and pelecypod shells, and partly from intraclasts in the sense of Folk (1962). These two categories of dolomite crystals are interpreted by the writer as resulting from a volume for volume replacement of calcite by dolomite, leaving therefore the shape of the original grain unaltered, or only slightly modified. The main reason for this interpretation is the presence of a small amount of quartz silt (less than 2 percent) which is sorted similarly to the surrounding dolomite, being very fine to medium silt-sized in the very fine to medium microcrystalline dolomite, and medium silt to very fine sand in the very fine crystalline to medium crystalline dolomite.

Unrecrystallized argillaceous dolomite is made up of small dolomite crystals very similar to the ones described above in laminated dolomite. They show the same reddish brown colour, and are sometimes partly masked by irregularly shaped lumps of argillaceous material (Plate II, Fig. 4). As mentioned

above, they must have originated as lime muds.

Occurrences of unrecrystallized dolomitized calcarenite are present in the Imperial Leduc 177 well. The grains are fine to very coarse sand in size, angular to well rounded. They are much more distinct in reflected light than in thin section, for they are constituted by a mosaic of smaller dolomite crystals (150 to 200 microns). The original nature of the grains cannot be ascertained because of the lack of internal structure; however, the writer believes that they are mainly of skeletal origin, with the possibility of a pelletal origin for the more rounded ones. The grains are encompassed by crystals of clear transparent dolomite, anhedral to subhedral, with a mean size of about 200 microns. These are interpreted as representing dolomitized sparry calcite; the alternative possibility, that of a dolomitized lime mud origin, was rejected because of the dissimilarity of this clear dolomite to the known very fine silt to mud equivalents, and because the texture of the rock, indicating rather turbulent depositional conditions, made the occurrence of mud very unlikely. Carozzi (1960) mentioned the fact that sparry calcite, after dolomitization, was likely to give a finely crystalline mosaic. An interesting progression can be observed from clusters of strongly pigmented crystals that retain the outline of the original grain, to loose assemblages of pigmented crystals amidst clear ones that are still recognizable as grains in reflected light, and to the final stage of alteration, a mosaic of crystals, some pigmented, some clear, with no visible structure.

Recrystallized constituents

These are found throughout most of the Nisku Formation surrounding the organic megastructures or making the bulk of thin structureless horizontal units. Their typical appearance in thin section is of a more or less tightly interlocked mosaic of crystals, 125 to 1000 microns in size, anhedral to subhedral

and rarely euhedral, angular, sometimes amoeboid (Plate II, Fig. 5). Pigmentation is highly variable from one crystal to the next and cannot be relied upon to give clues as to the origin of the grains. As mentioned above, pigmented crystals can represent skeletal debris, pellets, intraclasts, or recrystallized argillaceous dolomite. Brown pigment sometimes exhibits a rhombic pattern inside subhedral to euhedral crystals. The cause of this is not clear, although the occurrence has previously been mentioned (Kirmani, 1962). The writer's opinion is that, in the same way that a cluster of pigmented dolomite crystals inside a grain can be altered to an arrangement of scattered pigmented material amidst clear dolomite, the pigmented material is deformed during recrystallization so as to take a shape similar to the outline of the crystal.

Other constituents

Late-stage Dolomite

Throughout the Nisku Formation, but more particularly to the southeast, approaching the shelf type of deposition, there is evidence that the original sediment, after initial dolomitization, underwent a second phase of dolomitization along the fissures and fractures of what probably was a fully consolidated rock. The late-stage dolomite completely obliterated all features that might have resisted the first phase. It is generally restricted to a small volume paralleling the permeability channels, but does pervade larger parts of the core collected from the Futurity Weisener I well, on the southeast border of the Leduc field.

The late-stage dolomite is medium brown to grey-brown in reflected light and contrasts with the surrounding rock by its greater porosity. It is composed of crystals, 70 to 150 microns in size, mostly anhedral, angular, and rather closely packed. The fair porosity is the result of microscopic vugs in the absence of leached crystals or groups of crystals rather than of loose packing.

The crystals are fairly transparent, contrasting with the neighbouring pigmented ones that constitute the first stage dolomite (Plate II, Fig. 7). They seem to increase in size as they approach the unaltered dolomite and get farther from the anhydrite-filled fractures.

A subordinate number of the crystals exhibit euhedral faces. These crystals are found either in open voids or at the contact with the anhydrite.

Anhydrite

This mineral is found in two main forms. In places, numerous isolated crystals of anhydrite can be observed amidst the dolomite groundmass (Plate II, Fig. 6). They have a random distribution and are homeomorphic with the surrounding dolomite crystals. In some places they build up to 10 percent of the rock.

Another type of occurrence is in white masses, sometimes shapeless, more often espousing the shapes of the fractures and the vugs they fill. Two distinct crystal growth habits were observed in these masses. In the first one, the crystals are "brick-shaped" subhedral to euhedral, several millimetres in size and show the typical cleavage. In the second one, the anhydrite mass is composed of an aggregate of thin elongate crystals (for instance, 2 mm x 400 microns) and of microscopic crystalline fibers (for instance, 100 x 5 microns).

The anhydrite is later than the dolomite, for a few dolomite rhombs, partly altered to anhydrite, can be seen at the contact.

Euhedral isolated crystals can be seen in open vugs, but have no volumetric importance.

Silica

Quartz silt is particularly abundant in the upper third of the Nisku Formation. Its size varies from very fine silt to very fine sand. The grains

are very angular to subrounded, most of them being angular to subangular. They are generally well to very well sorted and give good indications as to the original size of the neighbouring dolomite material (Plate III, Fig. 2). Proportion of silt is always less than 2 percent in the Nisku sensu stricto, but attains 25 to 30 percent in the lowermost Calmar Formation (Plate III, Fig. 4). No overgrowths or authigenic quartz euhedra were observed.

A few silica fillings of leached Amphipora canals (Plate III, Fig. 3), and of stromatoporoid cavities can be observed. In the lower Nisku, sub-spherical chalcedony nodules, 200 to 400 microns in diameter, are relatively common.

Argillaceous material

Greenish grey in reflected light, this material appears reddish brown in transmitted light. It is commonly found as thin laminae and at stylolitic joints (Plate III, Fig. 5) where it accumulates as an insoluble residue. In argillaceous dolomite units, it is present as lumps and distorted elongate fusiform masses. X-ray diffraction analyses showed that the only clay mineral present is illite.

Pyrite

Pyrite is found as a minor constituent throughout the Nisku Formation. It occurs as groups of euhedral crystals in vugs, or as clusters of finely microcrystalline euhedral crystals in the dolomite mass. It seems to be concentrated preferentially in the more argillaceous parts and is often associated with organic matter.

Feldspars and micas

A few potash feldspars are associated with the quartz silt and have the same mechanical characteristics. Micas are present, but extremely rare. Heavy minerals are practically absent.

PLATE I

All photomicrographs were taken at a magnification of twenty-five times unless otherwise stated

1. Photomicrograph. Stromatopora ? sp. situated in Imperial Leduc 200 in the 5194-5195 feet below surface interval.
2. Photomicrograph. Tabular stromatoporoid showing a "comb-like" structure. Imperial Leduc 200, 5203 feet below surface.
3. Photomicrograph. Amphipora. Imperial Leduc 200, 5149-5150 feet below surface.
4. Massive stromatoporoid in growth position. Futurity Weisener I, 5229-5230 feet below surface.
5. Photomicrograph. Algal structure. Imperial Leduc 200, 5117-5118 feet below surface.
6. Algal structures. Imperial Leduc 200, 5113-5114 feet below surface.
7. Microphotograph. Transversal section of a dasycladacean. Imperial Leduc 200, 5190 feet below surface.
8. Thamnopora ? axial section. Futurity Weisener I, 5199 feet below surface.

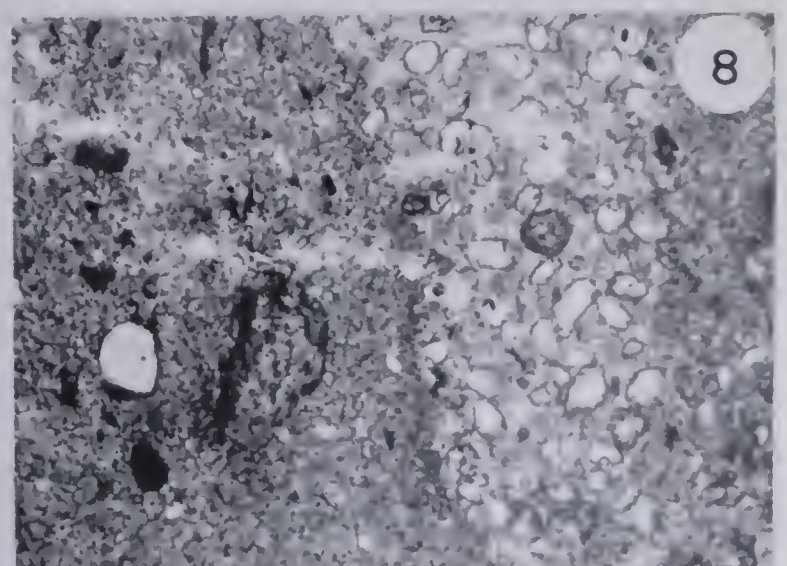
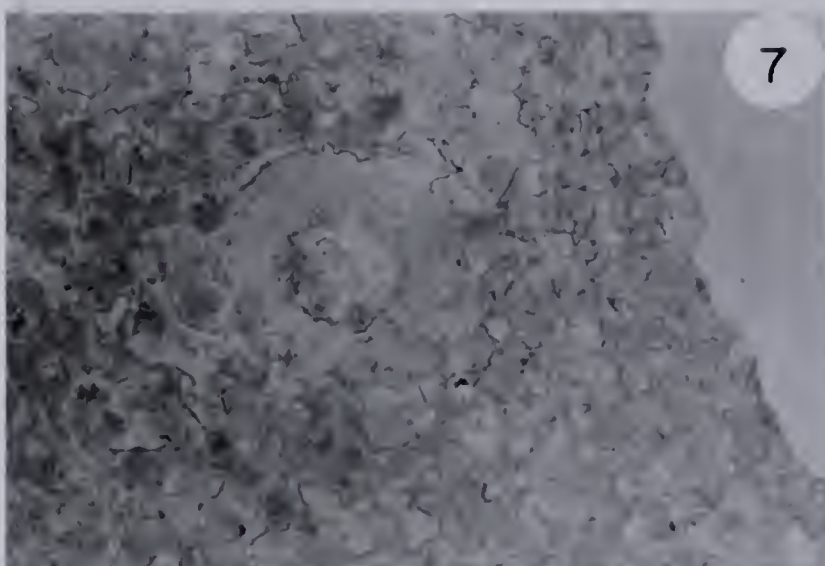
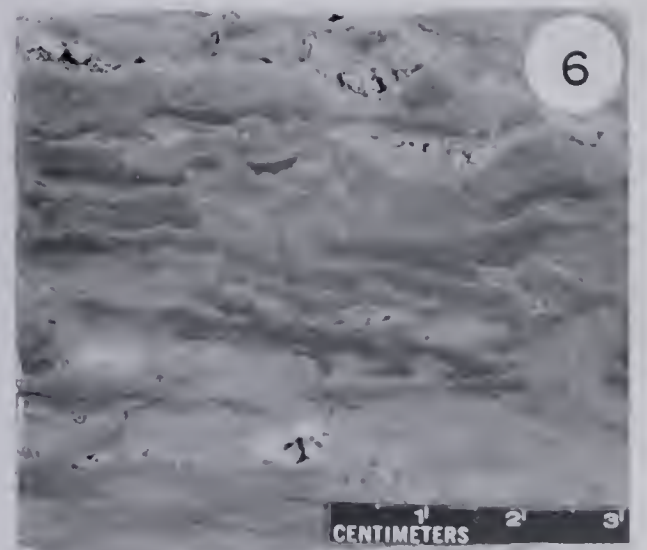
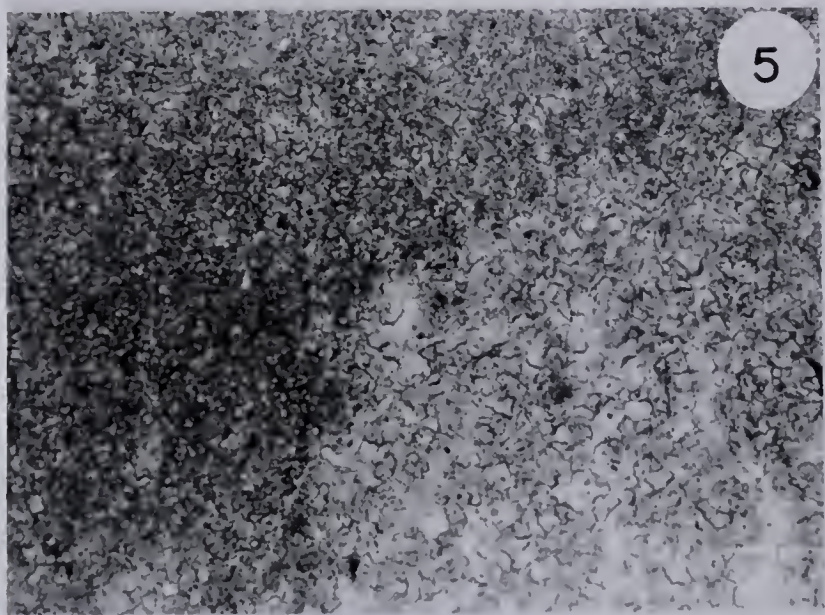
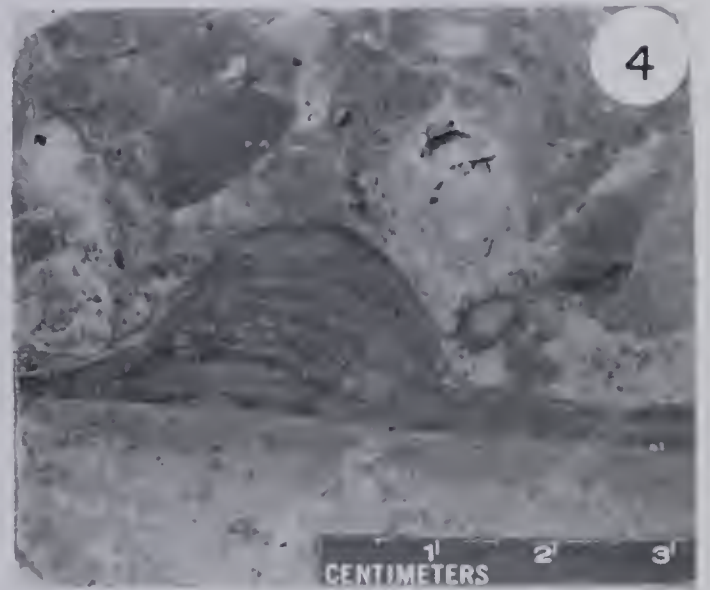
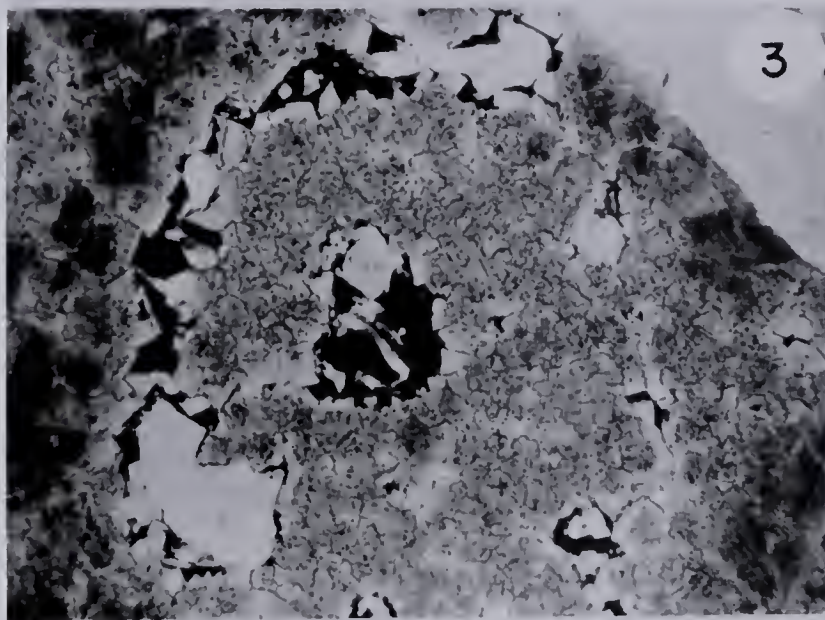
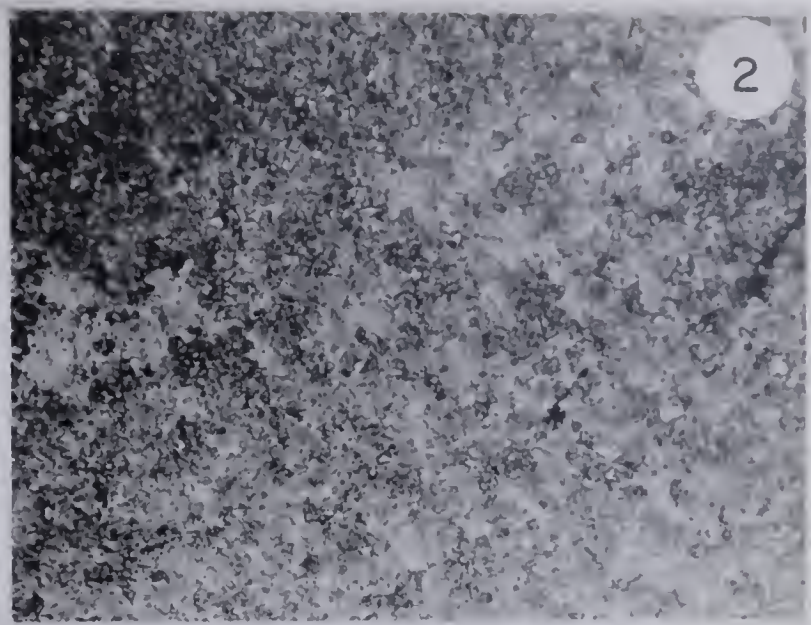
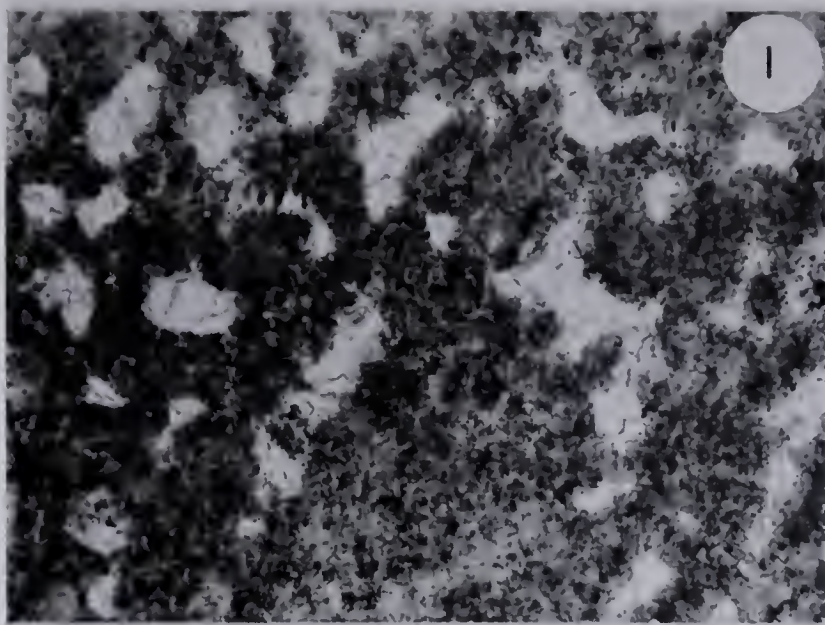


PLATE I.

PLATE II

All photomicrographs were taken at a magnification of twenty-five times unless otherwise stated

1. Photomicrograph. Brachiopod shell. Imperial Leduc 200, 5208 feet below surface.
2. Photomicrograph. Shell of unknown origin. Imperial Leduc 200, 5208 feet below surface.
3. Photomicrograph. Laminated dolomite. Imperial Leduc 200, 5114-5115 feet below surface.
4. Photomicrograph. Lumps of argillaceous dolomite. Futurity Weisener 1, 5157 feet below surface.
5. Photomicrograph. Nicols crossed. Recrystallized dolomitic silt. Imperial Leduc 200, 5183 feet below surface.
6. Photomicrograph. Nicols crossed. Isolated anhydrite crystal. Imperial Leduc 200, 5179 feet below surface.
7. Photomicrograph. Contrasting first stage (brown) and late stage (transparent) dolomites. Imperial Leduc 200, 5173-5174 feet below surface.
8. Photomicrograph. Contact between anhydrite and dolomite.

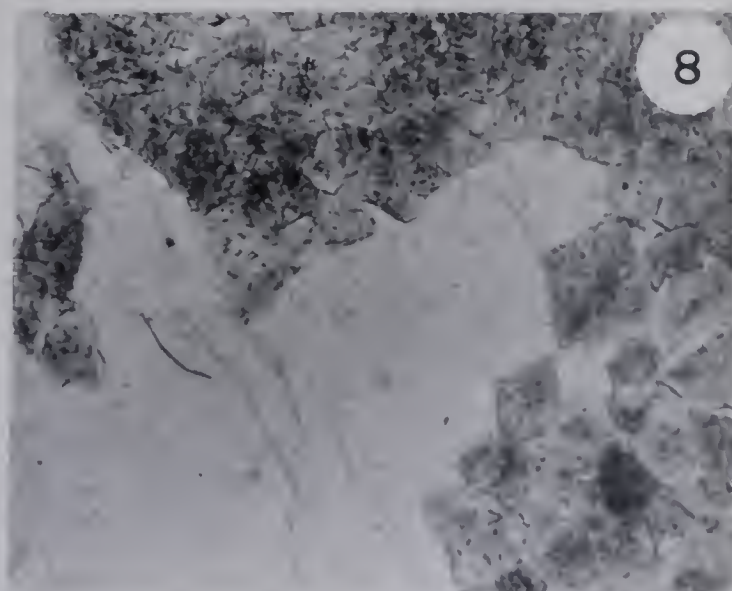
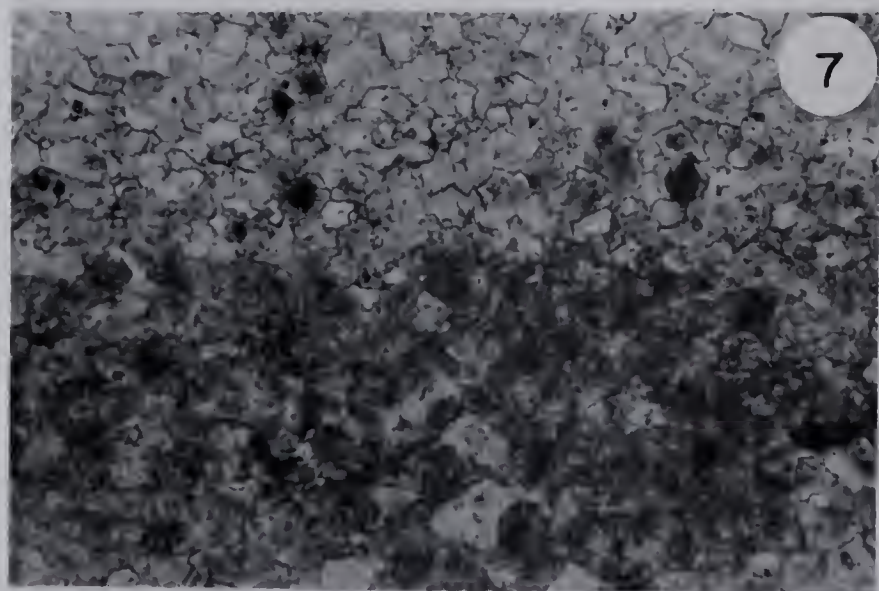
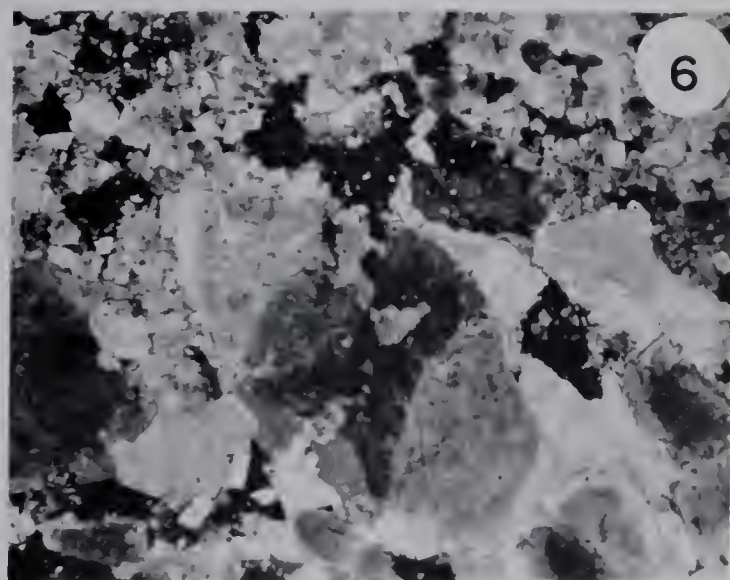
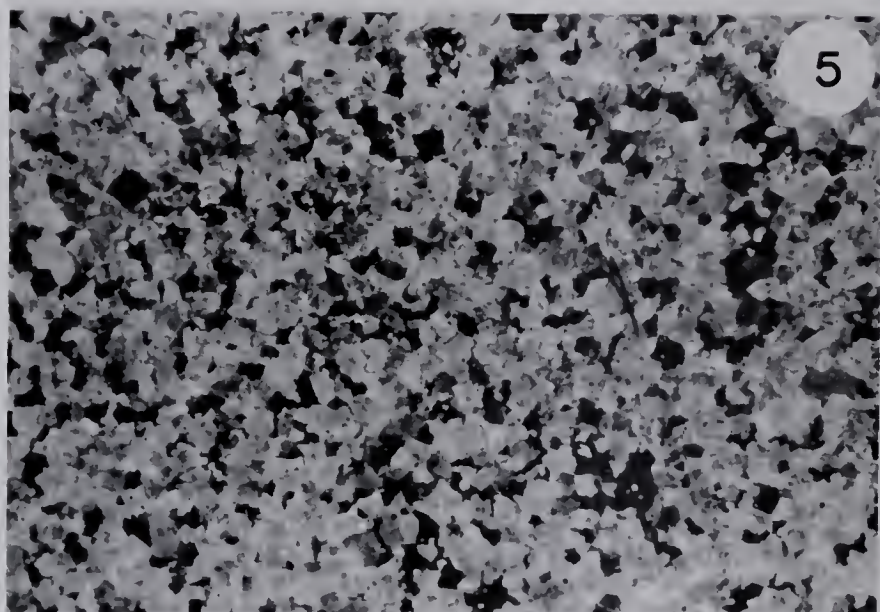
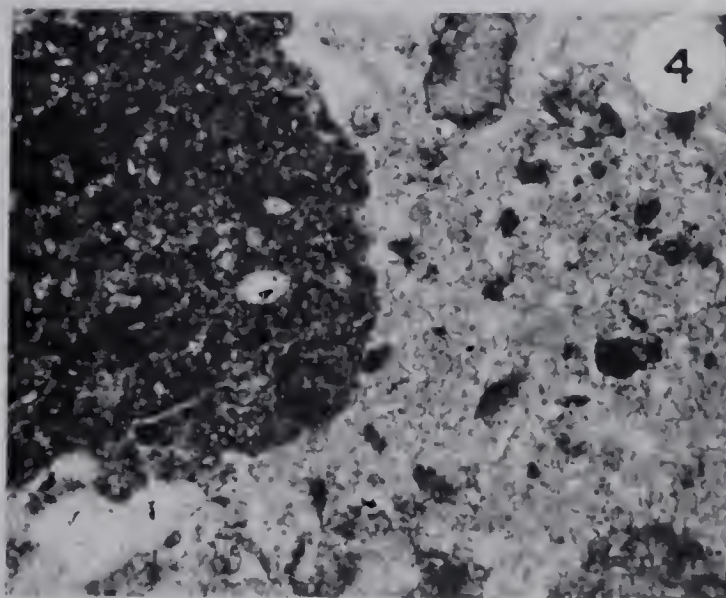
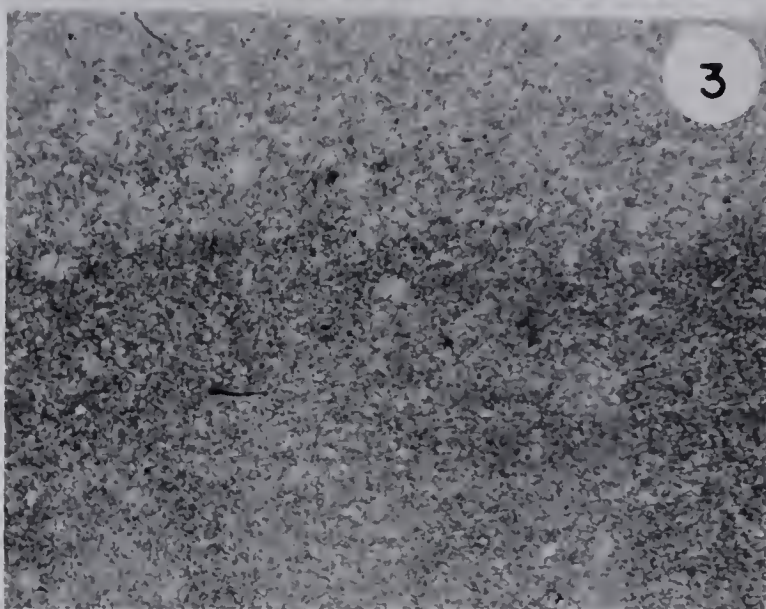
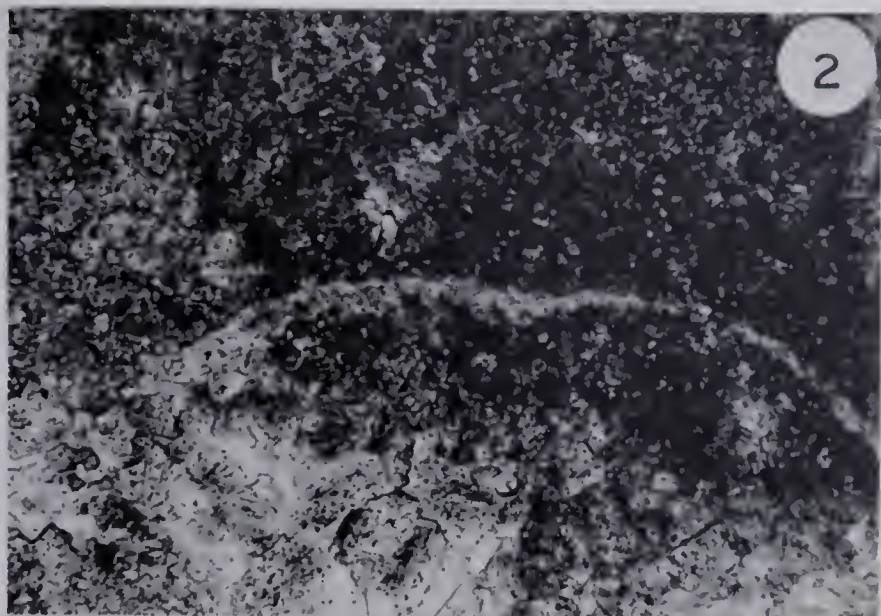
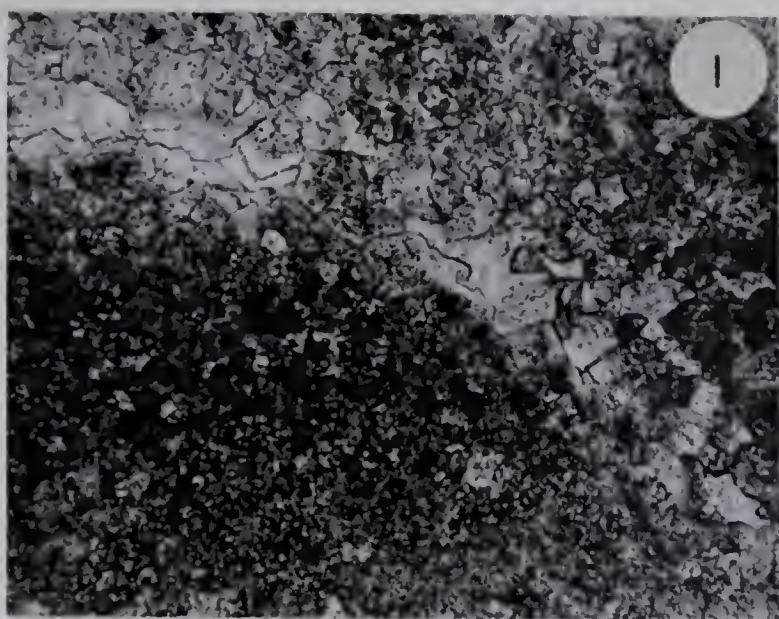
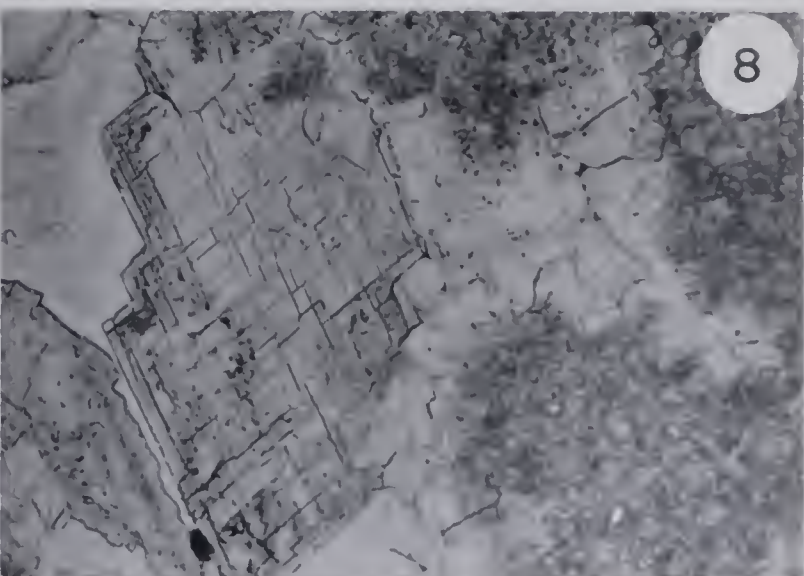
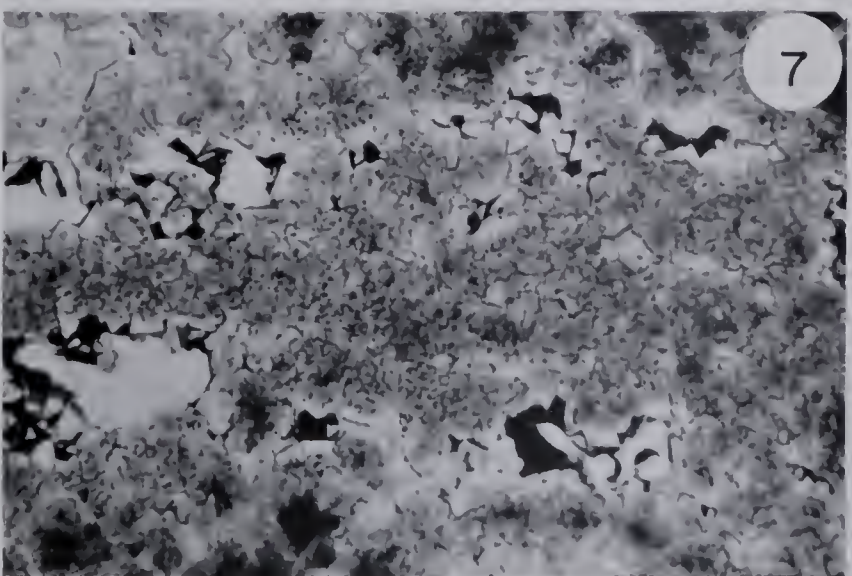
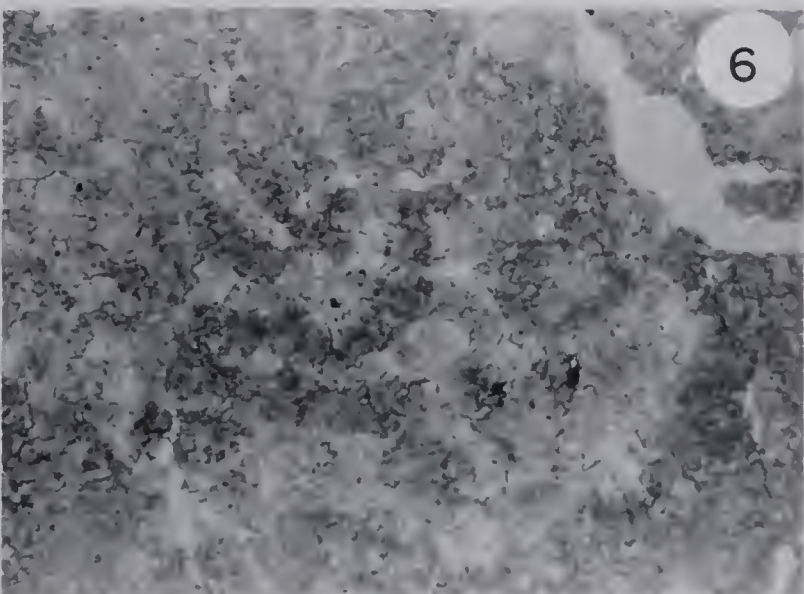
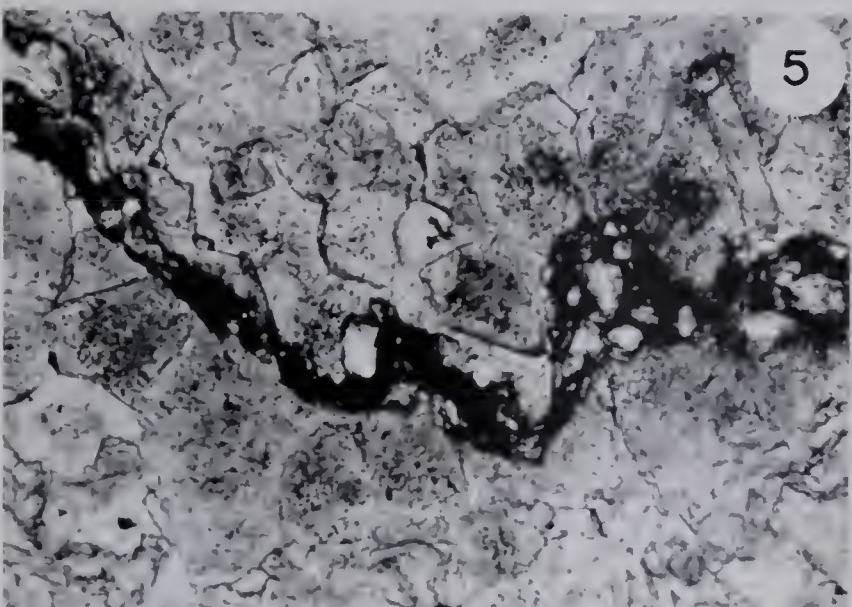
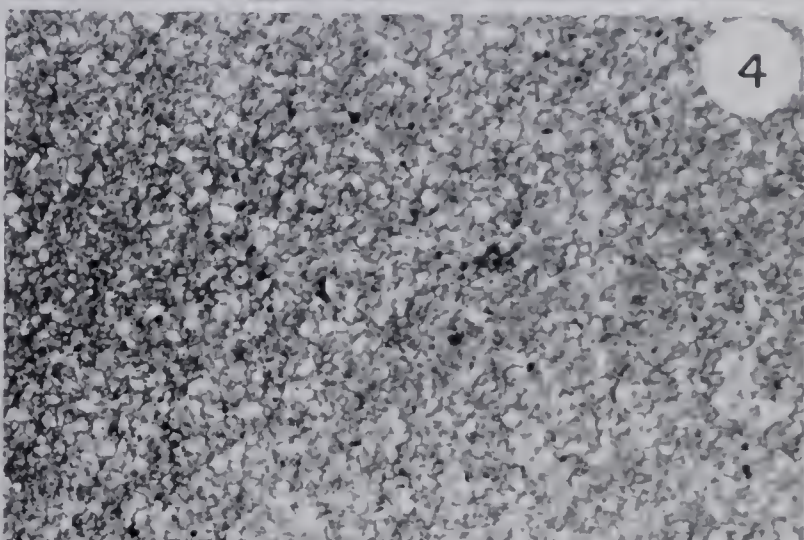
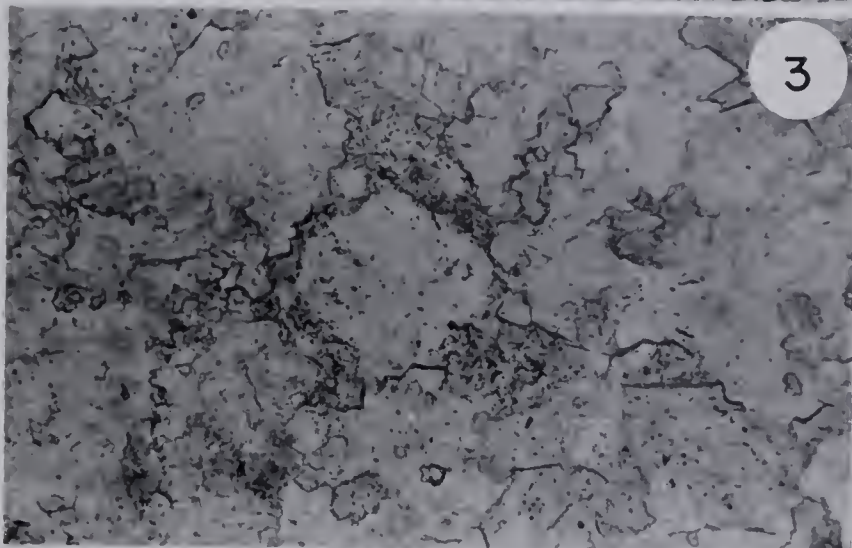
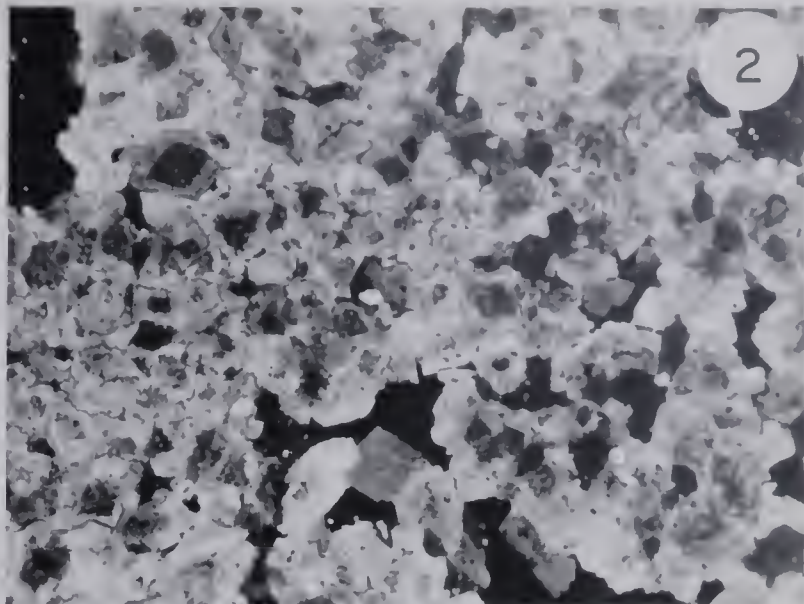


PLATE II.

PLATE III

All photomicrographs were taken at a magnification of ten times unless otherwise stated

1. Photomicrograph. Nicols crossed. Mixture of anhydrite crystals and microscopic fibers. Imperial Leduc 200, 5172 feet below surface.
2. Photomicrograph. Nicols crossed. Quartz silt scattered in the dolomite. Nicols crossed. Imperial Leduc 200, 5092-5094 feet below surface.
3. Photomicrograph (62X). Silica filling an Amphipora canal. Imperial Leduc 200, 5190 feet below surface.
4. Photomicrograph. Calmar dolomitic silt. Futurity Weisener I, 5140-5141 feet below surface.
5. Photomicrograph (80X). Argillaceous material in a stylolite. Imperial Leduc 200, 5121 feet below surface.
6. Photomicrograph. Dolomitized Amphipora still showing large, but blurred vesicles near its surface. Imperial Leduc 200, 5180-5181 feet below surface.
7. Photomicrograph. Black carbonaceous matter lining the voids leached out of an Amphipora. Imperial Leduc 200, 5149-5150 feet below surface.
8. Photomicrograph. Dolomite rhombs in a void. Imperial Leduc 200, 5208 feet below surface.



ECOLOGICAL SIGNIFICANCE OF THE FOSSILS

A consideration of the amount and nature of the fossils and fossil fragments yields some information as to the relative turbulence and organic productivity of the depositional environment. Encrusting or cemented forms associated with well sorted, well rounded calcarenites are indicative of the high energy conditions. On the contrary, vagrant forms surrounded by poorly sorted muddy sediments suggest quiet deposition. The importance of distinguishing between fossils found in situ and fossils which are washed in should be stressed. The problem bears heavily on the interpretation of fossil assemblages with respect to depositional conditions versus living environment. It is often very difficult to ascertain whether transportation of material such as Amphipora took place or not. Nevertheless, an attempt will be made to elucidate as clearly as possible the question of the post-depositional redistribution of the fossils.

It must be pointed out that the following discussion is based on observations made on three cores a few miles distant from one another. Although the control is far from sufficient to take into account lateral facies variations and variations in the abundance of the fossils, it is thought that the study effected gives an overall pattern of the palaeoecological and depositional conditions.

The fossils will be discussed in the order adopted for the petrography chapter.

STROMATOPOROIDS

Tabular stromatoporoids

These are abundant in the lowest Nisku, where they constitute up to 60 percent of the rock in places. They are much scarcer in the middle and

upper Nisku. Lithologies associated with tabular stromatoporoids range from slightly argillaceous to fairly argillaceous dolomite. When preserved, the matrix of these rocks is mostly constituted by medium to fine dolomitized calcisiltite. Constituent grains are subordinate (up to 20 percent of the matrix) and range in size from coarse to fine sand. The fossils associated with the tabular stromatoporoids are often well preserved, only slightly broken and do not exhibit evidence of important wear and abrasion. The stromatoporoids themselves are often found lying horizontally, sometimes ruptured by load action. In other instances, they are piled up in horizontally stratified or slightly inclined aggregates, separated by recrystallized calcisiltite and broken skeletons. In a few cases, the tabular stromatoporoids have been upturned and rolled.

Tabular stromatoporoids are associated with dendroid stromatoporoids, horn-shaped corals, dasycladacean algae and brachiopod and pelecypod shells.

As suggested by Klován (1963), these features indicate that tabular stromatoporoids lived preferentially in quiet water environments. The presence of broken debris of stromatoporoids could be explained by the intervention of limited periods of relatively high turbulence. Galloway (1957) has indicated that stromatoporoids could not compete with corals in quiet, muddy environments. The presence of abundant stromatoporoids associated with rare corals would indicate a relatively quiet type of deposition, with enough turbulence to favour the rapid development of the stromatoporoids.

Dendroid stromatoporoids

Amphipora is the organism encountered most frequently throughout the Nisku Formation. It is most abundant in the upper and the middle Nisku but is also an important secondary constituent in the lower Nisku.

Amphipora appears to have grown in a wide variety of environments.

In the lower Nisku, it is associated with the predominant tabular stromatoporoids, and is therefore present in what is regarded here as relatively quiet water deposits. In the middle and upper Nisku, it is abundant in rocks that show evidence of having been deposited in turbulent waters, for instance, in well washed coarse dolomitized calcarenites.

All the specimens being more or less fragmental, the growth habit of Amphipora is not well known. Specimens illustrating branching stems are rare, and no mode of attachment could be observed. The rule adopted to distinguish in situ Amphipora from bioclastic accumulations of skeletons was as follows: when branching stems could be observed pointing upwards, the organism was supposed to be in growth position; when, on the contrary, all the stems were broken and more or less parallel, the rock was considered to be biodetrital. Numerous horizons showed horizontally intertwined stems without vertically pointing branches; it is thought that this represents one of the growth habits of Amphipora, for transportation and sorting would not ordinarily result in stems crossing at right angles.

The depth influence seems to have markedly affected the growth of Amphipora. The specimens observed in the deeper water, more argillaceous, lower Nisku range in diameter from 1 to 3 mm, whereas the specimens from the shallower, well aerated upper Nisku range from 2 to 5 mm. Amphipora seems to have been more favoured by a well washed shallow environment, where it is the preponderant frame builder, than by the quiet muddy conditions that made tabular stromatoporoids proliferate and reduced it to a subordinate role.

Stachyodes fragments are rather rare. They are found scattered in the lower Nisku, in sediments indicative of a relatively high energy index. Of particular interest is a 10 cm thick stratum observed in the Imperial Leduc 177 well,

composed of loosely packed fragments of Stachyodes coenostea oriented with their long axes parallel to the bedding, which may be compared with the Stachyodes calcirudite described by Klován (1963). However, this bed probably is the product of a less turbulent depositional environment, since the fragments are rather loosely packed and embedded in a coarse calcarenite matrix.

Stachyodes was not found in situ and it is therefore difficult to infer from observation the mode of living of this organism. Klován (1963) indicated that Stachyodes lived in turbulent and moderately turbulent waters, and could have acted as a baffle for sediment movement. Branches of this genus could also have served to bind some of the sediment.

Stachyodes and Amphipora are found together in the lower Nisku, where the former is of very minor importance. In the middle and upper Nisku, the only recorded occurrence of Stachyodes is the above mentioned calcirudite. No Amphipora were observed in this stratum, although the Stachyodes calcirudite is overlain and underlain by an Amphipora calcirudite. It seems probable that Amphipora and Stachyodes are somewhat incompatible.

Massive stromatoporoids

As previously mentioned, massive stromatoporoids are extremely rare in the Nisku. They are found associated with the deposits of the lower Nisku that indicate a particularly high turbulence. Figure 4 of Plate I shows a dome-shaped stromatoporoid in growth position. It first developed on the surface of a fragmental calcirudite and extended as a thin widespread pancake-like organism. Later, the development of the skeleton was restricted to the central portion and the stromatoporoid expanded as a hemisphere. There is a sharp sedimentation break between the underlying calcirudite and the argillaceous poorly sorted rudite that surrounds the stromatoporoid.

The observations made on the few specimens present corroborate Klován's conclusions; namely, that massive stromatoporoids lived principally in turbulent water, and acted as baffles, thereby causing settling onto the sea floor of argillaceous sediments. The lack of data does not permit making a more detailed account of massive stromatoporoid ecology. For a more thorough study, the reader is referred to Klován (1963).

ALGAE

Algal structures are present, in limited numbers, in the upper and middle Nisku. It is not possible to identify the type of algae they represent, for, as previously mentioned, no microscopic texture remains. This is a result of dolomitization, and, probably, "grain-diminution" (Wolf, 1965).

Algal structures are often embedded in clear recrystallized dolomite, which could be interpreted as the end product of well washed fine to coarse calcarenite cemented with spar. Vugs are common and seem to have been even more abundant before dolomitization. Streaks of green grey shale interbedded with the clear dolomite are interpreted as the result of the baffle action of the algal structures. On the whole, these algae seem to have lived in well aerated waters, where currents washed the detrital material.

The relation of algae to *Amphipora* is complex. Where algal structures attain a development sufficient to act as rock builders, Amphipora is rare to absent. However, *Amphipora* as a rock framework is sometimes associated with encrusting algal structures.

Dasycladacean algae are found in the lower Nisku, associated with Amphipora and tabular stromatoporoids. They must have lived in the same type of environment as was favourable to these organisms. No growth habits or attachments were observed; it seems that most of the material is fragmental.

Klovan (1963) observed problematic dasycladacean fragments in the Cooking Lake equivalent deposits of the Redwater reef, sediments which seem in part to reflect depositional conditions roughly equivalent to those of the lower Nisku.

STROMATOPOROID-ALGAL CONSORTIUM

Very limited occurrences of this association occur in the lower Nisku. They develop generally in the proximity of tabular stromatoporoids, and indicate depositional conditions similar to the ones deduced from the study of these organisms.

CORALS

Solitary horn-shaped corals, found in association with tabular stromatoporoids, are so rare that little can be said concerning their preferred habitats. They are generally overturned but do not exhibit marked signs of abrasion.

Thamnopora, a dendroid tabulate coral is encountered in the Imperial Leduc 177 and Futurity Weisener I wells. Only broken and overturned fragments were observed, embedded with other organic debris in an argillaceous medium to coarse microcrystalline dolomite. The dolomite matrix, which contains 1 to 3 percent of coarse quartz silt in the Futurity Weisener I well is considered to have been a lime mud.

Previous palaeoecological work concerning Thamnopora (Wells, 1957 and Klovan, 1963) indicate that this coral lived in quiet to turbulent, well oxygenated waters. The specimens observed were probably torn out of their growth places by a temporary increase in turbulence, and dumped in muddy waters when the competency of the current that carried them became insufficient for their transport.

BRACHIOPODS AND PELECYPODS

These shells are most frequently observed in the lower Nisku, associated with tabular stromatoporoids and Amphipora. It is generally impossible to differentiate between brachiopod and pelecypod because of recrystallization and of the high degree of fragmentation of the shells. The living organisms probably dwelt on the soft muddy bottom where tabular stromatoporoids accumulated, but were later overturned and broken by the turbulence that occurred from time to time.

BURROWING ORGANISMS

In shaly dolomite strata it is possible to observe vertical or nearly vertical disruptions of the shaly and silty laminae that could be the result of the activity of burrowing organisms (Plate IV, Fig. 1). These vertical trails are characterized by an increase in the proportion of greenish grey silt and shale in comparison to the one observed in the whole rock. This could be explained as the result of fecal rejections of worm-like organisms. On the other hand, it is possible that these structures are the result of the escape of water under the increasing load of the overlying sediments.

PETROGRAPHIC FACIES OF THE NISKU FORMATION

GENERAL STATEMENT

Table 2 shows a specimen of the data sheet upon which lithologic and paleontologic data were recorded during the study. The data have been grouped into two main categories: external features, that is, the data that can be collected from direct observation of the core with the naked eye or the binocular microscope; and internal features that can only be observed with the help of thin sections and a petrographic microscope.

Lithologic facies were established by analysis of the data sheets and by visual grouping of rock types. It is felt that, although this method was adequate for the small number of cores studied, a more thorough study of the Leduc field would gain by the use of more sophisticated methods such as variance analysis and multivariate grouping of semiquantitative data. These methods could provide a wealth of information on the lateral variations of the rock types and on the paleogeography of the Nisku Formation. However, it is doubtful that they would permit a vertical subdivision of the Nisku more precise than the one observed here, which corroborates the study of Belyea (1955).

Fourteen rock types are recognized in the three sections studied, all of them but one dolomites, the exception representing the lowermost part of the Calmar Formation.

Figure 7 represents the reciprocal relationships that bind the facies, the contacts between adjacent rock-types being represented by lines joining the corresponding facies numbers in spacially distinct half-planes. Figure 8, a cross section of the Nisku Formation, shows their vertical and horizontal distribution. From the fourteen detailed lithologic units, six compound facies have been established to picture the main lithologic features. The detailed units can be

grouped as follows: the facies (1a), (1b), (1c) and (1d) represent most of the compound "Amphipora facies", which is characterized by a particular abundance of this fossil; the facies 2 and 3 are episodic, most commonly found as thin intervals surrounded by developments of the above mentioned units, and they are therefore included in the "Amphipora facies"; facies (4a) represents the largest part of the lower Nisku and constitutes most of the compound "tabular stromatoporoid facies"; facies (4b) is episodic and is included in more important compound facies; facies (4c), the "skeletal-pelletal - stromatoporoidal facies", found only in the well Futurity Weisener I, represents important intervals of this section and is regarded as a compound facies that peters out northwestwards; facies (5), the "argillaceous dolomite facies", can be correlated in the upper Nisku, from one end of the cross section to the other by geochemical methods, and is therefore regarded in this part of the Nisku as a compound facies, near the well Futurity Weisener I, it is associated with facies (4a) to constitute the compound "stromatoporoidal argillaceous facies"; the facies 6, 7, 8 and 9 are of local importance only, and are, when necessary, lumped together with more significant units.

The compound facies are easily grouped to form the three submembers established by Belyea (1955): lower, middle and upper Nisku.

The datum line chosen for Figure 8 is the top of the Nisku Formation, taken from the mechanical logs or, when it was possible, from petrographic and geochemical results. The top of the Ireton Formation was determined by the same methods.

TABLE 2
SPECIMEN OF DATA SHEET USED IN THE STUDY

EXTERNAL FEATURES

Lithology and colour

Impurities (shale inclusions, argillaceous lumps, etc)

Gross texture and structure (organic framework, laminated structure, etc)

Estimate of the percentage of fossils, their distribution and relative abundance

Secondary features: fractures, porosity, vugs, dissolution zones, anhydrite masses and late stage dolomite.

INTERNAL FEATURES

Mean grain or crystal size

Fabric, packing, assemblage of the crystals

Inferred original nature of the crystals

Anhydrite texture

Detrital material: nature, size, repartition in the sample, abundance etc.

MUTUAL RELATIONSHIPS BETWEEN THE DETAILED ROCK TYPES

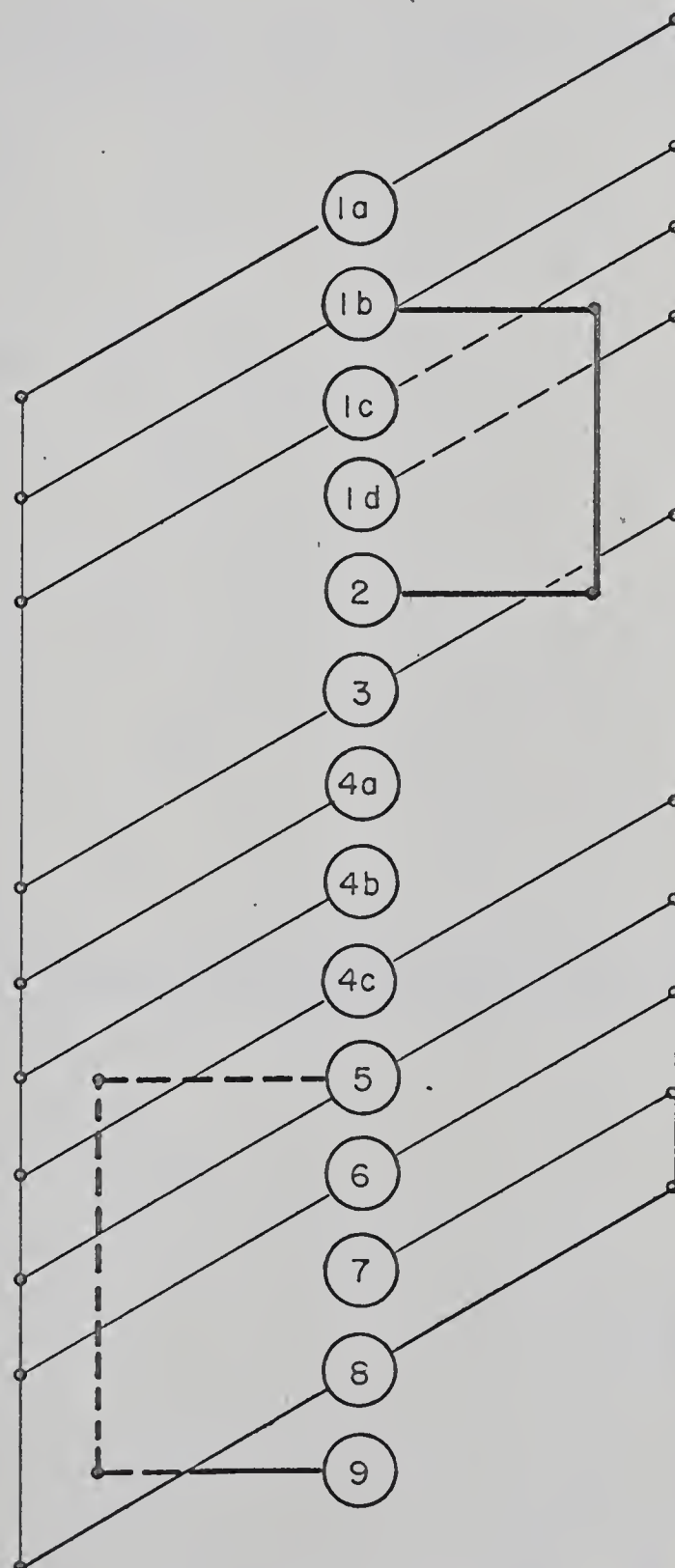


Figure 7.

NW.-SE. CROSS SECTION OF THE NISKU FORMATION IN THE LEDUC - WOODBEND OIL FIELD

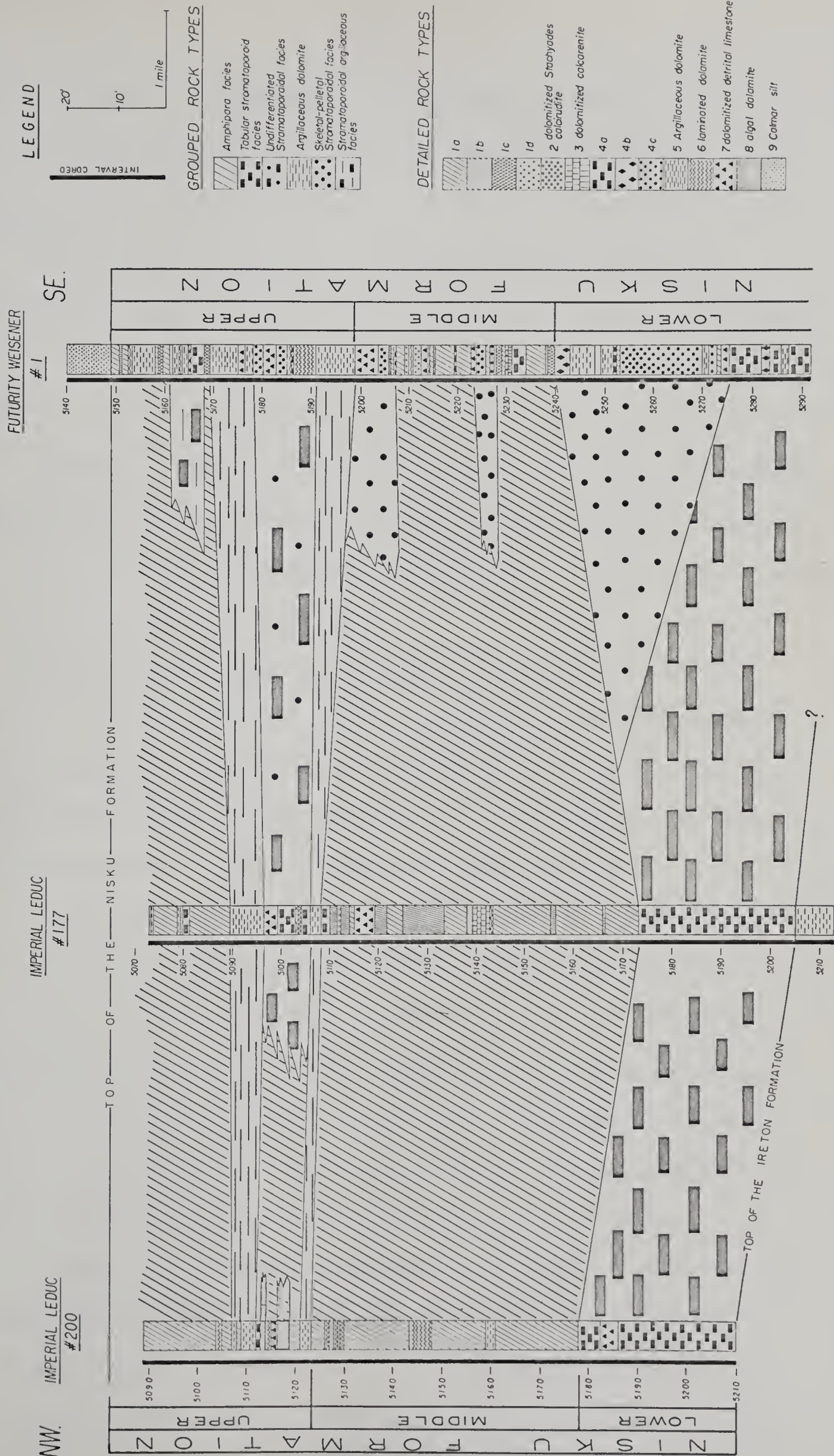


Figure 8.

DESCRIPTION AND INTERPRETATION OF THE PETROGRAPHIC FACIES

Facies (1a): dolomite (dolomitized skeletal - *Amphiporid* limestone)

Occurrence

This facies constitutes most of the upper and middle Nisku of the Imperial Leduc 177 and 200 wells; in the Futurity Weisener I well, it is subordinate.

Lithology

External - This is a light brown to medium brown dolomite, containing wavy green shale streaks and partings, often pseudo-stylolitic. Pyrite specks are rare, usually associated with carbonaceous or argillaceous material; a few euhedral pyrite crystals can be seen in open vugs.

Abundant specimens of Amphipora (up to 30-40 percent of the rock) characterizes this facies (Plate IV, Fig. 2). The stems are generally randomly oriented in the rock, and their length is not more than 3 to 4 centimetres. The surrounding rock is relatively tight and homogeneous when not leached. Wavy bands of various colours occur here and there, and are interpreted as of algal origin.

Fractures are rare. Porosity varies from poor to fair according to the amount of leaching. Amphipora stems are more sensitive to leaching than the surrounding rock, and the leaching is restricted to thin intervals. Dissolution is evidenced by a few stylolites and by the pseudo-stylolitic shale partings. Anhydrite is not abundant, and is mostly present as euhedral crystals in open vugs and as small white masses along the fracture lines. Porous late stage dolomite, yellowish to dark brown, occurs around some of the voids.

Internal - Surrounding the specimens of Amphipora, already described in the petrography chapter, the dolomite groundmass is composed mostly of recrystallized material. Both pigmented and transparent crystals are present, and they picture a tight mosaic. Crystal size is from 200 microns to 1 mm. The

likely derivation of this rock is from a largely skeletal calcarenite, encompassing non skeletal grains and very little mud. Secondary in volumic importance but particularly interesting are transparent patches found associated with open vugs and anhydrite masses: they are made up of mostly anhedral dolomite crystals, 80 to 120 microns in mean size, angular to subangular, rather loosely packed, with fair porosity due to the absence of crystals or groups of crystals. Crystal size becomes much smaller when approaching anhydrite, much greater when recrystallization occurs. It has been suggested that these patches could represent dolomitized sparry calcite.

Bituminous black films often line the vugs.

Interpretation

The rock of this facies shows the influence of four sources. Amphipora stems, often encrusted with algae, were broken after death and accumulated on the bottom near their place of life; sand-size skeletal debris was trapped by the broken stems and filled the open spaces between them; some subordinate silt-sized material and mud was deposited between the sand-sized grains; eventually, sparry calcite filled voids where the agitation of the water had prevented the accumulation of other debris. The environment must have been shallow enough to permit the development of algae, have been well oxygenated, and have had a normal salinity; the currents were strong enough to move coarse material, but could not overturn and abrade the Amphipora stems. Turbulence never increased to the point of depositing rudite beds.

It seems that this facies represents best the depositional conditions in an open marine, but shallow, environment during middle and upper Nisku times.

Facies (1b): dolomite (dolomitized skeletal Amphiporid limestone)

Occurrence

This facies is absent in the Imperial Leduc 200 well, very poorly represented in the Futurity Weisener I well; it reaches an important development in the middle Nisku of the central well, Imperial Leduc 177.

Lithology

External - This is a cream white to light brown dolomite, sometimes tinted pink or greenish by traces of argillaceous material. There is little shale, and it is concentrated as linings on the sides of the vugs or along stylolites.

As in Facies (1a), Amphipora is particularly abundant, apparently randomly oriented on horizontal planes. They give the impression of being more badly broken than in Facies (1a). Encrusting algae often deposit supplementary layers around the stems.

Fractures are absent; porosity is good, largely due to leaching of vugs (Plate IV, Fig. 3); dissolution is evidenced by a few stylolites. Anhydrite fills vugs with transparent euhedral crystals.

Internal - Grains are fine sand to very coarse sand in size, loosely packed, cemented with clear dolomite considered to represent dolomitized sparry calcite. They are skeletal and pelletal in origin, and their shape varies accordingly, angular to very angular for the skeletal grains, rounded to very well rounded for the pellets. An extremely small amount of fine to medium silt is found in the clear dolomite.

Interpretation

This facies shows the same influences as (1a). However, less advanced dolomitization permits making a less conjectural analysis of the depositional

conditions. The much greater porosity and the less interstitial ooze (greater "cleanness") in the sediment as well as the occurrence of sporadic calcarenite and even calcirudite beds, as in facies 2, indicate conditions of greater turbulence. The mud component was washed away, while the sand-sized particles, trapped or fanned down by the Amphipora stems, were cemented together by sparry calcite. The higher turbulence prevented vug filling by fine sediments and the mild ensuing dolomitization left most of these vugs open.

Facies (1c): dolomite (dolomitized detrital-algal - Amphiporid limestone)

Occurrence

This facies is found only in the Futurity Weisener I well where it constitutes a few beds in the middle and the upper Nisku.

Lithology

External - This is a variegated dolomite. A complex framework of small Amphipora stems, rare dasycladaceans and abundant algal encrustings is embedded in a dark brown matrix (Plate IV, Fig. 4). The framework is light brown to medium brown, tinted pink in places by traces of argillaceous material. In the matrix, small amounts of partly recrystallized and dolomitized calcarenite are concentrated in clusters.

No fractures were observed. Porosity is good because of abundant cavities in the framework. Unimportant anhydrite masses fill some of the voids.

Internal - The matrix is composed of partly recrystallized dolomite. Original size was 20 to 130 microns, and the recrystallized material reaches 500 microns. Recrystallized calcarenite grains show as medium to coarsely crystalline euhedra very loosely packed in the matrix.

Interpretation

Several factors conjugate to suggest that this type of rock corresponds to a rather quiet environment than those of facies (1a) and (1b): the small Amphipora specimens associated with dasycladaceans are, along with tabular stromatoporoids, indicative of rather quiet muddy deposition. This is confirmed by the presence of a silt-sized matrix. The calcarenite type sediment was from time to time washed in by an upsurge in turbulence, and deposited amidst the fine silt.

Facies (1d): dolomite (dolomitized skeletal - Amphiporid limestone)

Occurrence

This facies is limited to two beds, each about one foot thick, in the Futurity Weisener I well.

Lithology

External - This is a light to medium brown dolomite, apparently devoid of impurities. The general texture is of an Amphipora rudite; Amphipora stems represent up to 20 to 30 percent of the rock. Other fossils comprise a few broken tabular stromatoporoids and a variety of sand-sized skeletal debris.

Fissures are very rare and often filled with late stage dolomite. Anhydrite is unimportant, but may reach 5 percent in places. Porosity varies from poor to fair.

Internal - The Amphipora stems are encompassed by a complex arrangement of partly recrystallized dolomitized calcarenite and dolomitized sparry calcite. The calcarenite grains are believed to have been mostly skeletal.

The partial leaching of the Amphipora skeletons leads to the growth of dolomite rhombs in the voids thus produced.

Interpretation

This rock represents a level of turbulence slightly higher than those in facies (1a) and (1b). Amphipora stems were broken and transported, then deposited with abundant skeletal debris. The source area of the material may have been quieter, because of the association of Amphipora with a few tabular stromatoporoids.

Facies (2): skeletal dolomite (dolomitized Stachyodes calcirudite)

Occurrence

One single occurrence of this facies was recorded as a 10 cm bed in the Imperial Leduc 177 well, in the upper Nisku, surrounded by facies (1b).

Lithology

External - This is a light brown dolomite, devoid of impurities and of argillaceous material. The gross texture is that of a rudite, made of loosely packed Stachyodes stalks embedded in a fine to very coarse arenite (Plate IV, Fig. 5). The stalks are well sorted and measure about 3 to 4 mm across. A few thin tabular stromatoporoids are present.

Internal - The grains are subangular to well rounded, loosely packed, separated by clear transparent dolomite interpreted as representing dolomitized spar. The nature of the grains is difficult to establish because dolomitization has obliterated all of the internal structures. The writer feels that the grains are of both skeletal and pelletal origin, but is not able to estimate the relative proportions of each kind; however, the abundance of skeletons in the surrounding rocks makes it likely that the skeletal grains are in the majority.

Interpretation

The parallel alignment of the Stachyodes stalks and the relatively good

sorting and rounding of the embedding calcarenite suggest this rock is indicative of the most turbulent conditions encountered in the study. Stachyodes did not habitually grow in the environment in which this bed was deposited. We must suppose that the broken stalks were transported from a nearby place in an exceptional move, for instance during a storm.

Facies (3): dolomite (dolomitized calcarenite)

Occurrence

This facies is found in a four-foot interval in the middle Nisku of the well Imperial Leduc 177 and in a few 4-inches to one-foot intervals in the Futurity Weisener I well.

Lithology

External - This is a light brown dolomite, with very little impurities. There are no discernible structures, the grains being arranged in an isotropic fashion (Plate IV, Fig. 6).

The porosity varies from poor to fair. A few stylolites indicate the action of dissolution processes. Neither fractures nor anhydrite were observed.

Internal - The grains are fine to coarse sand in size, rather well packed, cemented with dolomitized spar. They are composed of dolomite crystals, 200 to 400 microns in size; very rare dolomite crystals are as small as 15 to 50 microns. The outlines of the grains are not distinct, even in reflected light, which makes their identification nearly impossible. They are believed by the writer to be mostly skeletal.

Interpretation

The only differences between this facies and (1b) is the absence of

Amphipora. It is thought that deposition took place under conditions similar to those deduced for (1b), but that, for reasons unknown, the environment was hostile to the growth of Amphipora.

Facies (4a): dolomite (dolomitized detrital - stromatoporoidal limestone)

Occurrence

This facies represents the lower Nisku in the Imperial Leduc 200 and 177 wells, as well as sizeable portions in the well Futurity Weisener I.

Lithology

External - This is a dark brown, slightly argillaceous dolomite, containing an important proportion of tabular stromatoporoids, algal encrusted Amphipora stalks, corals, dasycladaceans and Stachyodes, aligned in a more or less horizontal fashion (Plate IV, Fig. 8). The fossils are cream white to medium brown; the matrix is light-medium to dark brown. The proportion of fossils varies from less than 10 to more than 60 percent of the rock.

Fractures are present but not very common. In a few instances, there is evidence of local collapse of the consolidated rock. The porosity varies from poor to very good according to the abundance of vugs and to the nature of the matrix. Dissolution is not very important; a few stylolites and shale seams are present. Anhydrite is rather abundant in white masses; it constitutes up to 20 percent of the rock in places. Late stage dolomite is common and, in the Futurity Weisener I well, constitutes up to more than 30 percent of the rock.

Internal - The petrographic characteristics of the fossils have already been described. The matrix is often recrystallized. Unrecrystallized material shows the influence of three sources: argillaceous silt-sized crystals, representing a calcareous mud; sand-sized debris of shells and of skeletons, in places repre-

senting as much as 10 to 15 percent of the matrix; clear dolomite crystals, representing dolomitized sparry calcite.

Interpretation

The environment represented by this rock was quieter than any of those previously described. Tabular stromatoporoids grew in a quiet muddy environment associated with Amphipora, algae, and other fossils. After death, the fossils were slightly reworked by currents, and accumulated in vertical superpositions. Trapped by the skeletons, a considerable amount of argillaceous lime mud was deposited along with small amounts of sand-sized debris. Sparry calcite filled the spaces not occupied by the fine sediment. The whole picture is that of an immature sediment that was below wave base, but that must have been relatively shallow to sustain the growth of algae.

Facies (4b): dolomite (dolomitized skeletal-detrital-stromatoporoidal limestone)

Occurrence

This rock type is found in the middle Nisku of the Futurity Weisener I well.

Lithology

External - This is a light to medium brown dolomite, with very little impurities. It is a rudite, constituted by various skeletal fragments bigger than 2 mm, angular to very angular, and randomly oriented, embedded in a dolomitized calcarenite matrix (Plate IV, Fig. 7). The fragments represent tabular stromatoporoids, Amphipora, algae, intraclasts, rare massive stromatoporoids and possibly Stachyodes.

There are no fractures. A few very narrow fissures are filled with late stage dolomite. Porosity is good to fair. Anhydrite fills vugs, rarely accompanied by late stage dolomite.

Internal - The fragments of fossils are embedded in a loosely packed medium to coarse dolomitized calcarenite. The sand-sized grains are cemented with spar and silt-sized grains.

The intraclasts are found in a silt-sized mud, light brown in reflected light, containing a lesser proportion of fossils than the type described above.

Interpretation

This facies is a detrital accumulation of broken pieces of the elements found in the preceding one. It represents an upsurge in turbulence which broke skeletons of fossils and transported them along with an important quantity of sand-sized and silt-sized particles. The more turbulent waters offered favourable conditions for the growth of massive stromatoporoids. The whole process must have taken place below principal wave base, as is indicated by the very poor sorting of the debris.

Facies (4c): dolomite (dolomitized skeletal-pelletal-stromatoporoidal limestone)

Occurrence

This facies is found only in the Futurity Weisener I well, where it constitutes about a third of the lower Nisku; it occurs sporadically in the middle and upper Nisku.

Lithology

External - This is a dark brown, slightly argillaceous dolomite. No impurities or shale lumps were observed. It is a rudite with debris of Stachyodes, Amphipora, algae, a few tabular stromatoporoids and oncolites. Around the fossil debris are sand-sized dolomitized grains. The fragments are not worn or abraded, and are concentrated in parts of the rock.

Fractures and fissures are filled with late stage dolomite which in places pervades most of the rock. There is little anhydrite except where the rock is broken; then anhydrite fills the voids, reaching about 10 to 15 percent of the rock.

Internal - The grains are very fine to coarse sand-sized, rounded to sub-rounded, poorly sorted and well packed. Their origin is probably pelletal and skeletal. Patches of partly recrystallized clear dolomite, encompassing rare dolomite silt, are interpreted as dolomitized sparry calcite in association with dolomite growth in former voids.

Interpretation

This type of deposition must be intermediary between those of (4a) and (1b). The presence of argillaceous material and of tabular stromatoporoids indicate a deeper environment than that of (1b); the preponderance of sand-sized grains, the presence of Stachyodes and Amphipora, of oncolites, indicate the action of currents more powerful than the ones in (4a). It must have been a moderately deep environment, yet one where the circulation of the water was relatively powerful.

Facies (5): argillaceous dolomite

Occurrence

Two argillaceous intervals separated by 15 to 30 feet were correlated between the three wells. They occur in the Upper Nisku, the lower one marking the base of this submember, which is the horizon where a sharp change in quantity of detrital quartz is observed. Argillaceous dolomite can be found throughout the cores studied, and it does not seem to be a facies diagnostic of a particular water depth. It is present at the top of the Ireton Formation, supposed to have been deposited in relatively deep water, as well as the top of the Nisku at the contact

with the Calmar, a formation generally considered to have been deposited in very shallow water, bordering on the continental.

Lithology

External - This is an argillaceous dolomite, coloured brown to greyish green in reflected light, and sometimes tinted red. Argillaceous lumps and pyrite bodies are commonly found. The pyrite aggregates may cover an area of more than 3 cm².

The feature diagnostic of this facies is the presence of a sizeable amount of argillaceous matter, which is shown by X-ray diffraction analysis to be illite. The rock is laminated (Plate V, Fig. 1) or exhibits long shreds of green silty argillaceous material, flame structures, lumps, contorted rolls, broken laminae, or appears as a simply structureless mass.

Fractures, rare in the Futurity Weisener I well, are common in the Imperial Leduc 177 well where they are filled with anhydrite. Porosity of the rock itself is negligible, but fractures increase the permeability. In a few places, there is evidence of load brecciation after lithification. Dissolution, evidenced by the shape and the concentration in some argillaceous bands, seems to have been minor.

Internal - The general grain size is silt. The laminae are made up of fine silt-sized dolomite alternating with coarse to very coarse silt-sized dolomite; in every lamina some quartz silt of the same size as the surrounding dolomite is found. Another mode of occurrence of the argillaceous material is in irregular lumps, containing very little detrital quartz, encompassed by dolomite silt rich in quartz. Broken fossils may be associated with the latter type of occurrence.

The argillaceous material cannot be distinguished with the petrographic microscope. As a residue, it is greenish grey in reflected light, made up of sub-microscopic particles. No heavy minerals could be obtained from the residue.

Interpretation

Very few fossils are found in the argillaceous dolomite. Its high detrital content indicates an increased influence of terrigenous deposition, which may have been achieved in two ways: by an increase in the rate of erosion of the nearby land, or by a drop in the production of calcareous material, caused by a slow down of the biotic activity. Both conditions may have been active and related, for an environment rich in silt and clay was probably not favourable to the life forms of the Nisku.

The lamination encountered indicates the action of weak traction currents that would sort the material on the sea bottom. Subsequent load pressure and the escape of the water contained in the fresh sediment would distort and even disrupt some laminae, causing the well known flame structures. Slumping and the dynamics of water saturated sediments can explain the structures found in this facies. The action of burrowing organisms such as worms cannot be discarded however.

Facies (6): laminated dolomite

Occurrence

This facies, present in all three wells studied, is confined to the middle and upper Nisku. It occurs in small intervals, always less than a few feet thick, and is found alternating with several other facies, among which (1a) and (1b) are preponderant.

Lithology

External - This is a variously coloured dolomite in reflected light.

Generally light brown to dark medium brown, it takes on a greenish hue when argillaceous material becomes relatively important, and is sometimes tinted red by microscopic red flakes whose true nature remains unknown. Impurities are

wavy, horizontal shale partings and, in places, microscopic pyrite specks.

The main diagnostic feature is the presence of regularly alternating, differently coloured laminae of contrasting grain size. Evidence of cross lamination is sometimes present.

No fractures were observed. The porosity is intergranular, varying from negligible or poor in the finer grained sediments, to fair in some coarsely crystalline laminae. Anhydrite is rare, and is only found as plugs in the voids, thus reducing the porosity. Dissolution is shown in the coarser laminated dolomite by pseudostylolitic shale partings (Plate V, Fig. 5).

Internal - Grain size varies much depending upon recrystallization. Consideration of the detrital material and of the unrecrystallized grains led the writer to the opinion that the original sediment was mainly silt-sized. The origin of the grains cannot be ascertained; they were probably skeletal grains and intraclasts.

Interpretation

This rock type represents moderately shallow deposition, in depths comparable to those of Facies (1a) and (1b). Fine grained sediments, collected from the degradation of nearby fossils and from the sea bottom, were sorted by gentle currents that could divagate, as indicated by the cross bedding. The absence of coarse material indicates that this process took place below the wave base. This rock is considered to be a by-product of the fossiliferous build-ups of other facies.

Facies (7): dolomite (dolomitized detrital limestone)

Occurrence

This rock type is found in the three wells studied as rather thin intervals (always less than 5 feet) alternating with various other facies; it is found throughout

the Nisku Formation and is probably not indicative of a particular water depth.

Lithology

External - This is a dark brown dolomite with very few impurities. There are no observable structures. Fossils are absent to rare, and are mostly Amphipora.

A few fractures, filled with late stage dolomite and a little anhydrite, make the rock somewhat permeable, but the matrix is tight. A few stylolites indicate the action of dissolution phenomena.

Internal - The groundmass is a homogeneous mosaic of dolomite crystals, anhedral, 100 microns across in the mean. They are moderately pigmented and, in the great majority, recrystallized. Unrecrystallized silt-sized grains are encompassed by recrystallized ones. It is felt by the writer that this groundmass is the equivalent of silt to fine sand-sized calcareous sediment; the grains were mostly non-skeletal in origin, rather a lime mud encompassing small intraclasts.

Interpretation

This facies corresponds to very quiet settling conditions which were hostile to all life forms except possibly Amphipora. The absence of currents led to a structureless accumulation of grains in a stagnant, poorly oxygenated milieu.

Facies (8): algal dolomite

Occurrence

This facies is found as a few beds reaching a thickness of two to three feet in the upper Nisku of the Imperial Leduc 200 and Futurity Weisener I wells.

Lithology

External - This is a light to medium-dark brown dolomite in reflected

light. Horizontal greyish green shale seams are present, and the vugs contain euhedral pyrite crystals. The main gross features are conspicuous algal bandings, nearly horizontal, with some elongate vugs showing the growth of dolomite rhombs and of anhydrite euhedra (Plate V, Fig. 2).

Very narrow fissures are filled with late stage dolomite, wider ones by dolomite rhombs. The porosity is good, mainly because of the vugs. Dissolution does not seem to be important, and neither do anhydrite fillings.

Internal - Algal structures, that constitute up to 30 percent of the rock, are surrounded by a partly recrystallized, coarser crystalline dolomite, containing some detrital quartz silt. The original calcareous material was supposedly silt-sized.

Interpretation

This rock type is found amidst rocks indicative of a rather shallow environment. The size of the sediment trapped by the algae, and of that surrounding them, establish that this rock type corresponds to quiet muddy depositional conditions. The algal developments exclude any other fossils, which seems to indicate some kind of incompatibility between the environment represented by this facies and the more common ones illustrated by facies (1a) and (1b).

Facies (9): Calmar dolomitic silt

Occurrence

The single observed occurrence of this facies is at the top of the core collected from the Futurity Weisener I well. It was separated from the Nisku on obvious petrographical and geochemical grounds.

Lithology

External - This is a greyish green argillaceous dolomitic siltstone. No

special structure can be observed, except the vague alignment of horizontal grey lumps.

There are no fractures and no anhydrite. Porosity is extremely poor, for the rare vugs do not communicate. There is no evidence of dissolution phenomena.

Internal - The quartz silt is 30 to 100 microns across, anhedral, subrounded to angular; its mean size is about 70 microns. The proportion of quartz is 30 to 40 percent with a few potash feldspars.

Encompassing the quartz is a dolomite groundmass with a bimodal size repartition: bigger crystals are the same size as the quartz, smaller ones range from 1 to 15 microns. All these crystals correspond probably to a calcareous material that was of similar texture.

Interpretation

This facies follows upward an occurrence of facies (1a). It indicates a radical change in the depositional conditions. The Nisku type of life was "silted out" by a tremendous increase in the rate of deposition of terrigenous material. The kind of topography causing this phenomenon is not known. The absence of current or wave marks in the sediment seem to indicate that the deposition was effected in a quiet environment; a possible type of environment would be a sheltered lagoon, separated from the open sea by a subaerial flat. Life forms would be inhibited by the restricted conditions and by the excessive rate of terrigenous deposition.

DEPOSITIONAL HISTORY OF THE NISKU FORMATION

Following Ireton deposition, the lower Nisku is characterized by the considerable development of the "tabular stromatoporoid facies", which constitutes most of the lowest parts of the three cores examined. Conditions were relatively

deep, but not deep enough to bar the growth of algae, muddy and rather quiet. Weak currents could transport tabular stromatoporoids, the most abundant fossils, for short distances, wash some sand-sized particles along gullies and keep some of the voids open where sparry calcite was later precipitated, thus giving an immature sediment. This picture is particularly characteristic of the two north-westerly wells which are situated in a region where the Leduc Formation exhibits an important reefal build-up. In the southeasterly well, which was drilled in a place where no Leduc reef is present, after a start similar to the ones previously described, the lower Nisku deposition changes to the "skeletal-pelletal - stromatoporoidal facies". It indicates a more turbulent environment than the one just described.

The middle Nisku is characterized by the overwhelming preponderance of the "Amphipora facies". Conditions were notably shallower than before, but the turbulence was rarely high enough to break and sort the fossils. Amphipora proliferated in well oxygenated, well agitated waters, and furnished the framework of the loose sediments, mostly sand-sized, that constitute the submember. The action of currents washed away the fine fraction and kept the voids open for the subsequent precipitation of sparry calcite. Temporary breaks in the depositional pattern permitted the occurrence of subordinate intervals of mud, laminated dolomite, or dolomitized calcarenite. There too, the Futurity Weisener I well, at the southeast border of the field shows some variations from the pattern described above which applies mostly to the more open environments. Intervals of "Amphipora facies" alternate with intervals of "tabular stromatoporoid facies", of "skeletal-pelletal - stromatoporoidal facies", and of mud. It seems that the more terrigenous sedimentation evidenced in this well caused the Amphipora to be supplanted from time to time by other fossils, better adapted to a high proportion of argillaceous material.

The upper Nisku is defined by an increase in silica content due to the

greater proportion of quartz silt (Belyea, 1955). Two argillaceous dolomite horizons could be correlated in the three wells by geochemical analysis (see the Geochemistry chapter). The lower one is taken to be the base of the upper Nisku, because of a sharp increase in silica content. Between the two argillaceous horizons lies a complex zone, about ten feet thick. It is characterized by algal structures in the Imperial Leduc 200 well, but in the two other wells it contains mainly tabular stromatoporoids, mud, and laminated dolomite. If the algal structures are taken to represent a quiet, muddy environment, then this interval could mean a temporary deepening of the sea bottom bringing conditions favourable to tabular stromatoporoids and blue-green algae. Above the second argillaceous horizon, conditions are similar to those of the middle Nisku, causing the preponderance of the "Amphipora facies", with, in the southeast, the influence of terrigenous source which causes the occurrence of thin intervals of facies (4a), (8) and of argillaceous dolomite.

Calmar sedimentation, observed for a few feet in Futurity Weisener 1, contrasts sharply with the preceding types. Preponderant terrigenous material was deposited in a quiet shallow basin, where life was practically non-existent.

DIAGENESIS

The following discussion will deal with the changes undergone by the Nisku sediments after their deposition; the various processes will be discussed separately and not as a chain of events since their exact chronological succession is not accurately known. The main diagenetic processes having affected the Nisku Formation are: dolomitization, deposition of anhydrite, recrystallization, compaction and solution, silicification, pyritization and biotic activity.

Dolomitization

The first stage dolomitization was effected by a volume for volume replacement process, as is indicated by the calcarenite grains, whose outlines are still preserved, and by the fossils. Aphanocrystalline to very fine microcrystalline calcite was converted to medium to very coarsely microcrystalline dolomite, while the sparry calcite resulted in very fine to fine crystalline dolomite. This trend toward equalization of the grain size is general, as was noted by Carozzi (1960). After the initial conversion of calcite to dolomite, the growth of transparent dolomite crystals between those constituting the grains eventually resulted in a structureless mosaic of pigmented and of clear crystals, where the outlines of the grains completely disappeared. This process did not affect the fossils, which seem to be more resistant to alteration, to the same degree. The alteration of calcite to dolomite was supplemented by the growth of dolomite crystals in the voids at the contact with sea water; these appear as rhombs, when the voids are still open, or as a mosaic of transparent dolomite filling previous canals, fissures and vugs, with a grain size similar to that of dolomitized sparry calcite.

Several processes have been invoked in the past few years to explain dolomitization. None of them, in the writer's opinion, could have applied

during Nisku sedimentation. There is no indication of "seepage refluxion" (Adams and Rhodes, 1960), or of emergence of an algal flat (Illing and Wells, 1964), or of lagoonal deposition (Alderman and Von der Borch, 1963). Fairbridge (1957) mentioned the case of the Funafuti atoll, where calcareous sediments are suddenly dolomitized at a critical depth under the ocean level; it is possible that a similar phenomenon, associated with changes in pH (Sass, 1965) could have taken place at shallower depths during Calmar time.

The late stage dolomitization is obviously related to the permeability network that was established after lithification. Sonnenfeld (1964) points out that magnesium sulfate in solution can react at relatively low temperatures with calcium carbonate, in the presence of anhydrite, to form dolomite if the overburden is at least 2,100 feet. A reaction of this kind is considered to be responsible for the formation of late stage dolomite. The excedent calcite along the fractures would have been dolomitized, and some crystal equilibration process would have altered the first stage dolomite in contact with the later one until an equilibrium was attained. This must have taken place long after the deposition of the Nisku, if we have to accept the notion of an overburden of 2,100 feet; however, this can be reduced by the intervention of catalysts such as ammonium salts and free carbon dioxide (the products of plant decay) to the more plausible thickness of 700 feet, which would permit an age as early as late Wabamun time.

Deposition of anhydrite

As mentioned before, there are two main kinds of anhydrite deposits: Isolated crystals homeomorphic to dolomite grains: these are interpreted as replacements of dolomite by anhydrite. The alternative explanation would be the sedimentary formation of gypsum crystals, later converted to anhydrite. This

type of occurrence is limited to supratidal flats in arid climates, or to desertic playas (Murray, 1964); neither of these environments can be evidenced in the Nisku Formation.

The white anhydrite masses are considered to be the result of both void filling and replacement. Good examples of void-filling anhydrite are displayed by the first type of white masses: large subhedral clear crystals, filling the pre-existing spaces. The second type of white masses is more complex. Its contact with the dolomite often shows the replacement of some dolomite crystals (Plate V, Fig. 3); late stage dolomite frequently lines the anhydrite; the anhydrite exhibits a multitude of very small crystals, among which are bigger ones, which suggests some non equilibrium, chill-like process. If magnesium sulfate-rich solutions are responsible for the formation of the late stage dolomite, it may be conceived that former void-filling anhydrite would have been affected by the reaction; in addition to this, the circulation of the extremely saline solutions would have favoured some dissolution of the carbonates, and non equilibrium replacement anhydrite would have been added to the former one, thus greatly increasing the proportion of anhydrite in the rock.

Recrystallization

The dolomite crystals have a definite tendency to group to form larger crystals, often subhedral to euhedral (Plate V, Fig. 4). This is what is meant by recrystallization. It is found in all types of crystals and does not affect preferentially certain size groups. Extremely fine material (1 to 10 microns) forms granoblasts 70 microns across, while more commonly sized crystals (70 to 150 microns) recrystallize as 500 to 1000 micron grains.

Recrystallization is caused by a re-arrangement of the crystalline material in the solid state: the free energy stocked in the crystals can be sub-

divided into volume free energy and surface free energy; while the volume free energy is the same per unit of volume in a large and in a small crystal, the surface free energy of a cluster of small crystals is much greater than the surface free energy of a large crystal of equivalent volume, because the total of the areas of the small crystals is much larger than the area of the single crystal.

Compaction and solution

Compaction due to the weight of overlying sediments can greatly reduce original pore space, thus contributing greatly to lithification. However, most of the Nisku rocks, reinforced by a strong skeletal framework, do not exhibit evidence of great compaction. The Amphipora stalks, surrounded by sand-sized sediment, resisted the weight and are not crushed. Tabular stromatoporoids are sometimes broken by differential load, but, even as large-sized debris, were enough to strengthen the sediment and help it keep its original structure. The argillaceous dolomite was the rock that was most affected by compaction; evidence consists of very rare intraformational conglomerate, of the wavy aspects of fine silt laminae, and of the contorted structures common in this rock type.

Solution effects are more common and more widespread than compaction ones. They are evidenced by stylolites and more common microstylolites (Plate V, Fig. 5), found generally in the rocks of the "Amphipora facies". As a rule, dissolution attacks and washes out the carbonate fraction, leaving in its place the argillaceous one. The total loss of thickness due to dissolution was not measured, but is estimated to be a few percent only. Of particular interest is the preferential location of some stylolites at a lithologic break, separating two contrasting petrographic facies.

Differential leaching attacks solely Amphipora stems in some parts of the "Amphipora facies", leaving the surrounding rock mostly unattacked (Plate V,

Fig. 6). The causes of this phenomenon are not well understood. Weyl (1960) proposed a theoretical scheme for the conservation of porosity in dolomites, based on the establishment, during dolomitization, of a compaction resistant dolomite framework, which would enable the rock to keep a constant volume during the leaching processes. It is possible that the sediment mass that surrounds the Amphipora stems could have, after lithification, played a similar role. In this case, we would have to admit that, by their own nature, the Amphipora stems are more sensitive to leaching than the rest of the sediment, a hypothesis which should be considered with regard to their different dolomitic structure. Another embarrassing problem is that of the sporadic and seemingly erratic occurrence of the leached zones; no explanation could be devised by the writer.

Silicification

In addition to the detrital quartz silt of the upper Nisku, silica replacements take place in the lower Nisku. They occur as crystals filling Amphipora or tabular stromatoporoid canals and as subspherical nodules 200 to 400 microns in diameter. The association of silica with the canals indicates the active intervention of formation water; a mechanism similar to the one proposed by Siever (1959) might have precipitated silica in the permeability channels. The formation of nodules may have been triggered by the presence of chert seeds precipitating silica from aqueous solutions. Nodules are generally surrounded by non-porous dolomite, which indicates that their formation probably took place before dolomitization. The origin of the silica may have been sponge spicules, although no such structure could be observed because of dolomitization.

Pyritization

Pyrite is found in vugs or as clusters of crystals in the massive rock. It is known that pyrite forms in reducing conditions just under the sediment-water interface. Hydrogen sulfide, released by organic decay, combines with iron to give pyrite. The association of pyrite with organic matter and with argillaceous facies, propitious to anaerobic fermentation, confirms this origin.

Biotic activity

Benthonic organisms such as worms and holothurians are capable of overturning and disturbing sediments, thus destroying primary features. In addition to this, worms pass sedimentary material through their digestive systems, leaving behind them coprolitic structures. Biotic activity may be responsible for some of the contorted structures found in the argillaceous dolomite.

PLATE IV

All photomicrographs were taken at a magnification of twenty-five times unless otherwise stated

1. Vertical disruption in laminated argillaceous dolomite, possibly the result of biotic activity. Futurity Weisener I, 5174 feet below surface.
2. Acetate peel (1X) of a recrystallized amphiporid dolomite (facies 1a). Imperial Leduc 200, 5153 feet below surface.
3. Acetate peel (1X) of a porous, partly leached, amphiporid dolomite (facies 1b). Imperial Leduc 177, 5128 feet below surface.
4. Photograph of a variegated dolomite (facies 1c). Futurity Weisener I, 5239 feet below surface.
5. Photograph of a Stachyodes rudite. Imperial Leduc 177, 5111-5112 feet below surface.
6. Acetate peel (1X) of a dolomitized calcarenite (facies 3). Imperial Leduc 177, 5141-5143 feet below surface.
7. Photograph of a skeletal rudite (facies 4b). Futurity Weisener I, 5229-5230 feet below surface.
8. Photograph of a dolomite mainly composed of tabular stromatoporoids (facies 4a). Imperial Leduc 200, 5206 feet below surface.

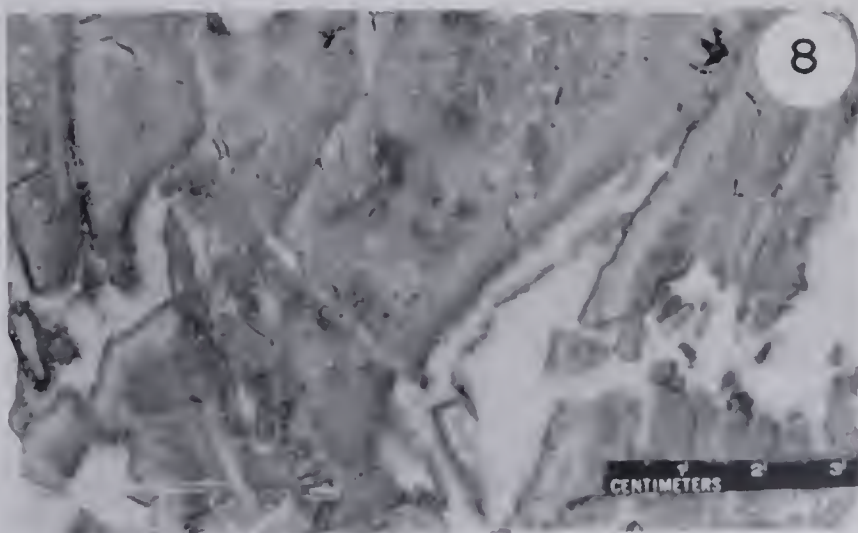
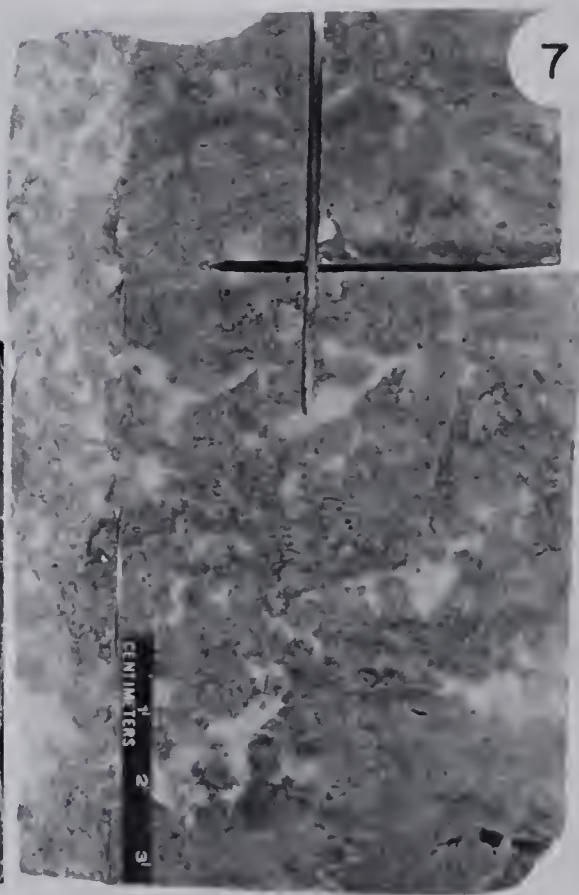
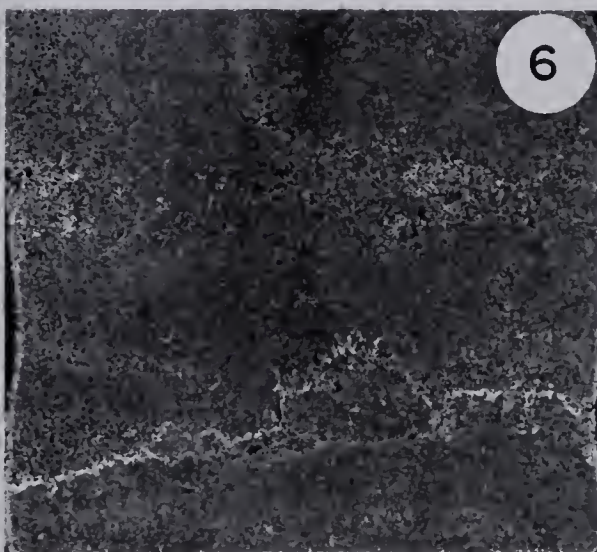
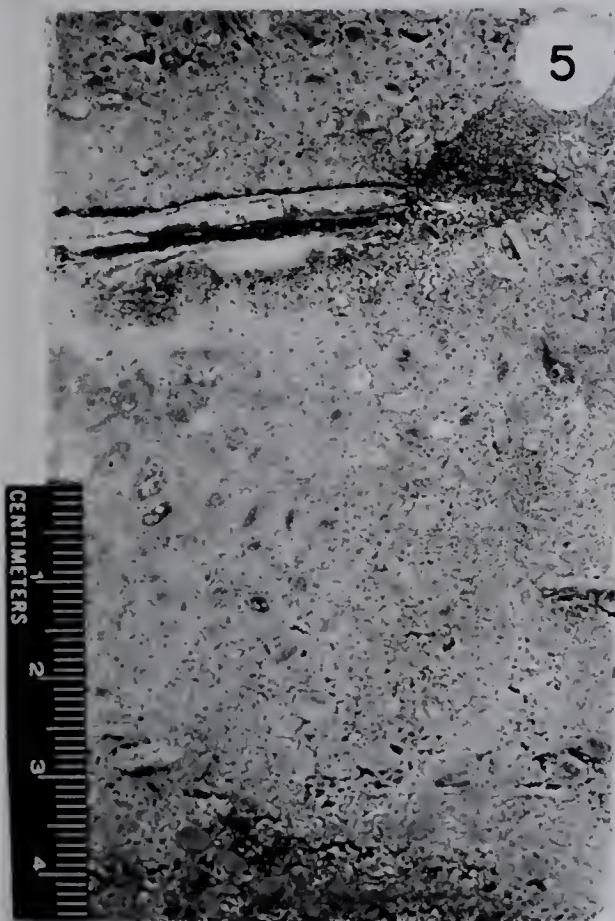
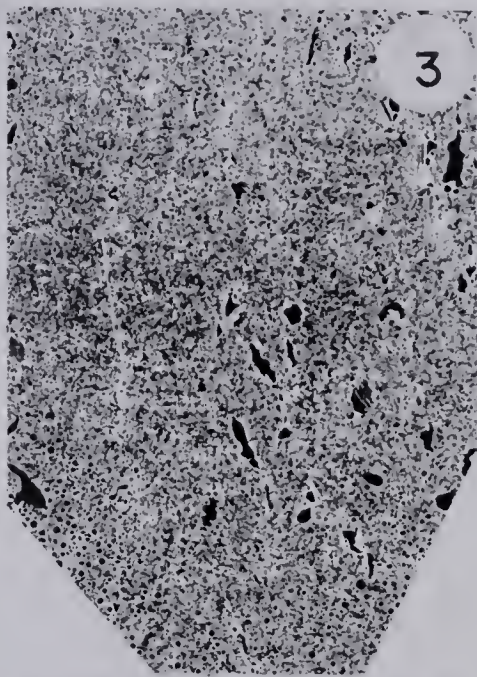
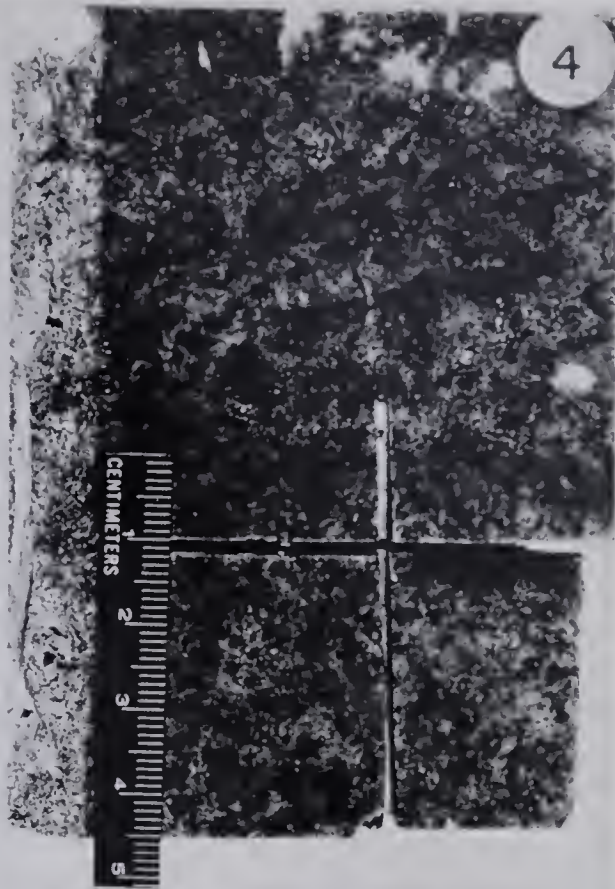
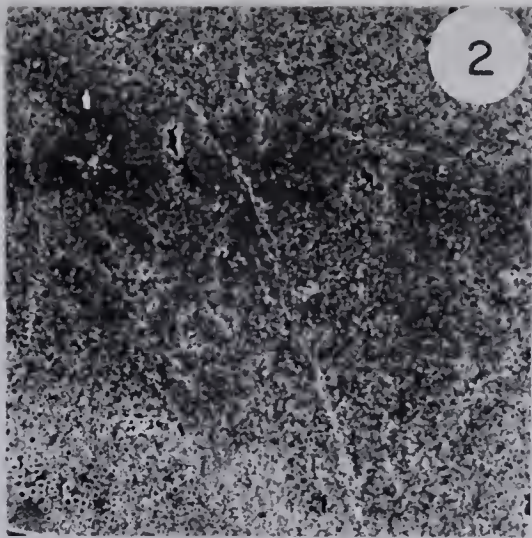
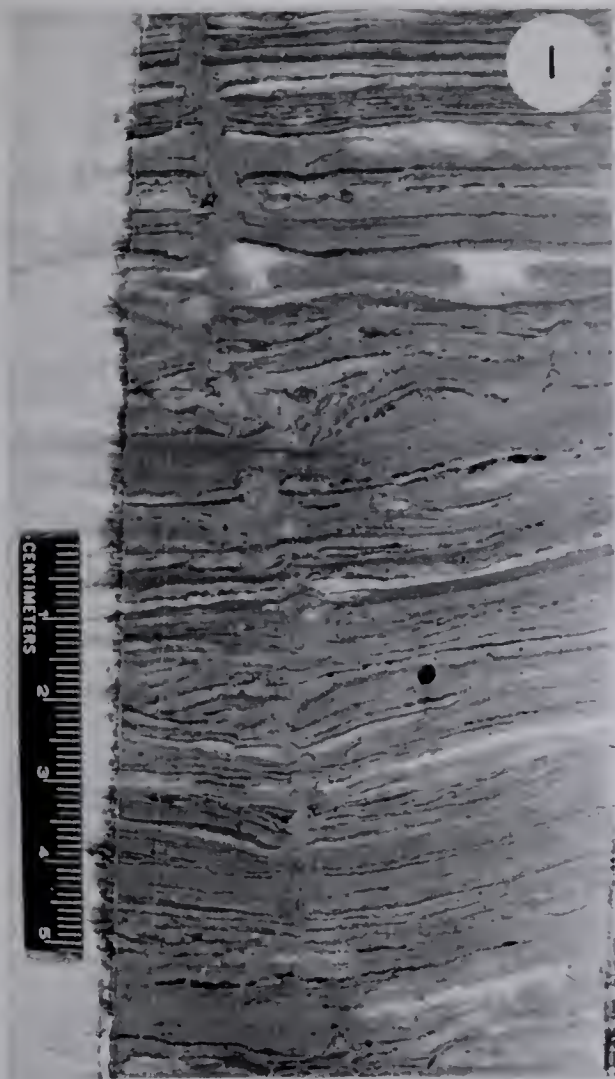


PLATE IV.

PLATE V

All photomicrographs were taken at a magnification of twenty-five times unless otherwise stated

1. Acetate peel (1X) of an argillaceous dolomite (facies 5). Futurity Weisener I, 5174 feet below surface.
2. Acetate peel (1X) of an algal dolomite (facies 8). Imperial Leduc 200, 5113-5114 feet below surface.
3. Photomicrograph (62X). Anhydrite replacing the inside of a dolomite rhomb. Imperial Leduc 200, 5149-5150 feet below surface.
4. Photomicrograph. Nicols crossed. Recrystallized dolomite surrounding a dasycladacean stem. Imperial Leduc 200, 5190 feet below surface.
5. Photomicrograph. Microstylolite. Imperial Leduc 200, 5143-5144 feet below surface.
6. Photomicrograph. Nicols crossed. Leached Amphipora. Imperial Leduc 200, 5139 feet below surface.

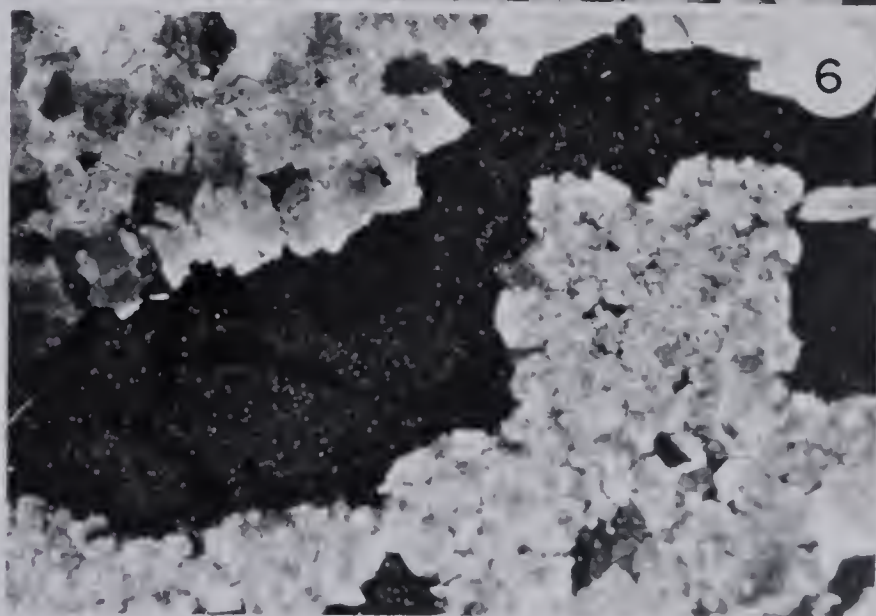
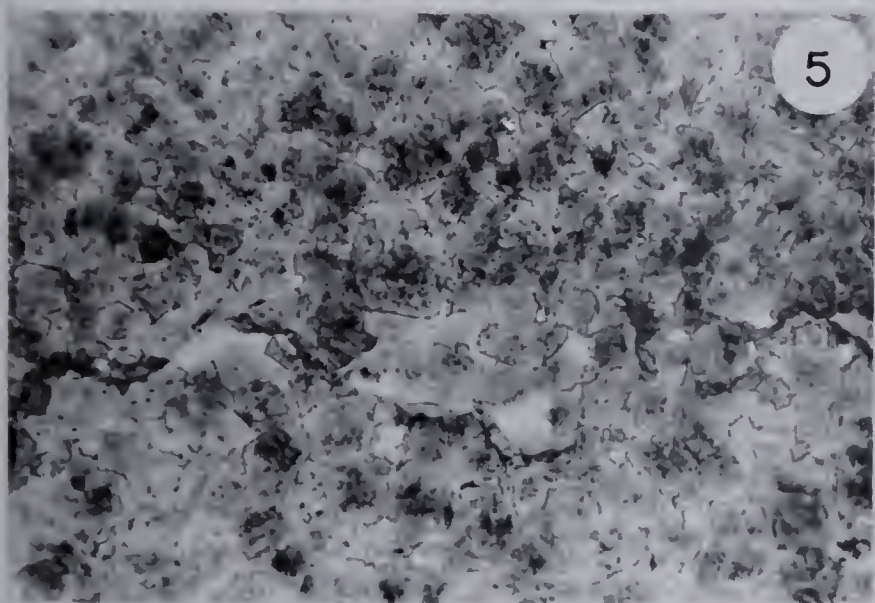
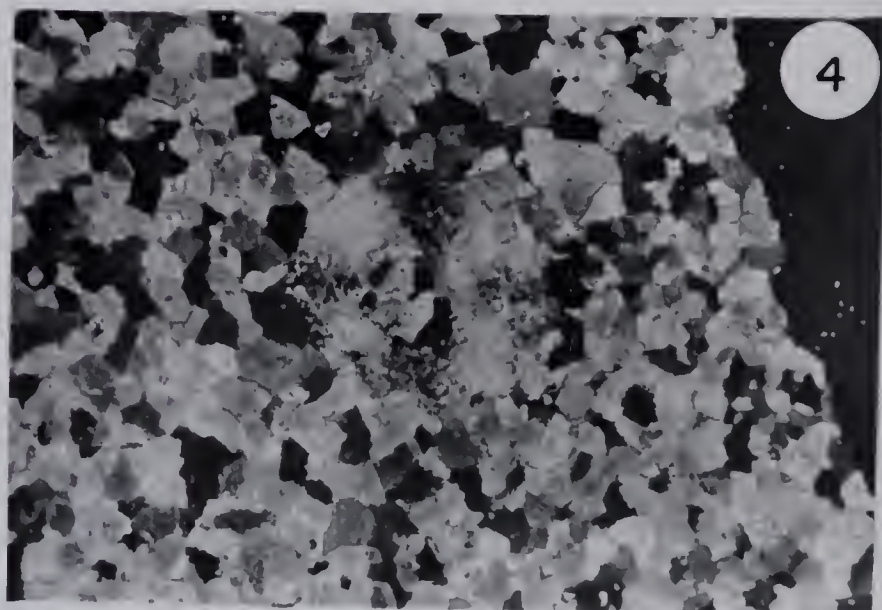
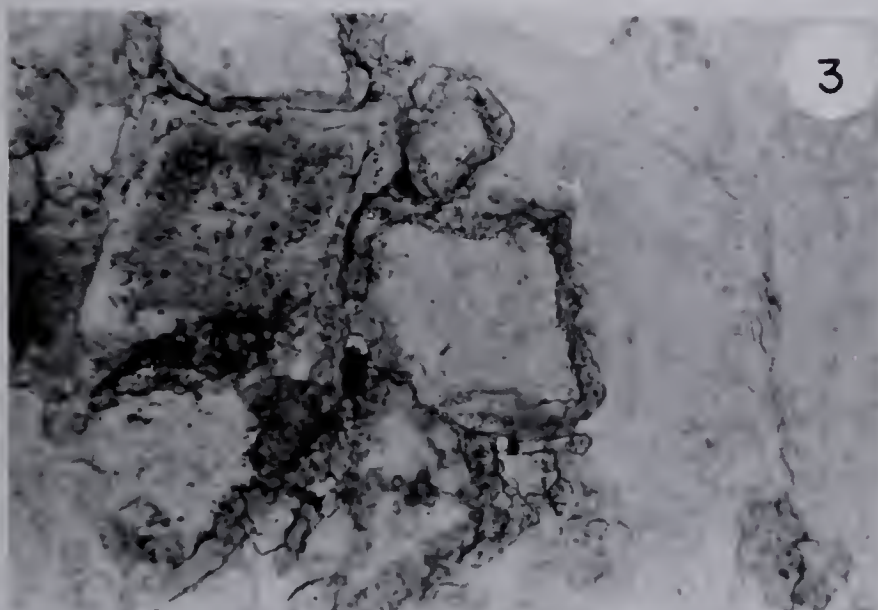
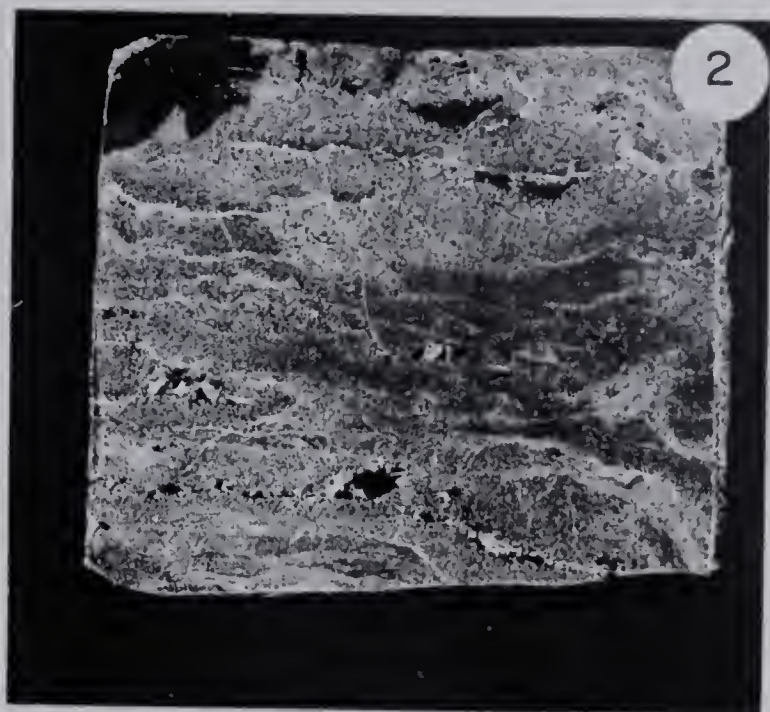
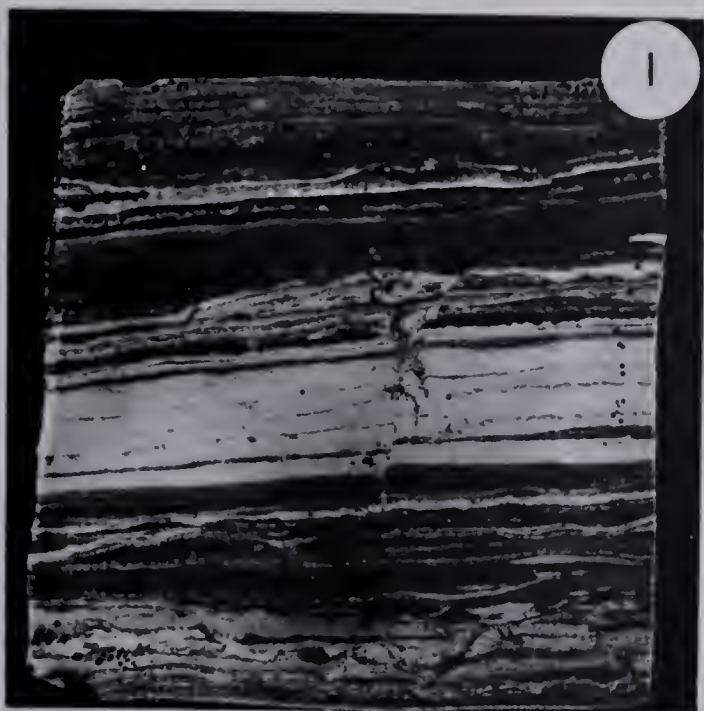


PLATE V.

GEOCHEMISTRY

GENERAL STATEMENT

Campbell and Lerbekmo (1963, 1965), Weber (1964a, 1964b) and many others have stressed the importance of the chemical analysis of carbonates for purposes of stratigraphic correlation, petrographic investigation and for a better insight into the processes of dolomitization.

It was decided in the present study to analyse the cores on hand by the X-ray fluorescence method and to compare the results of the analyses with those of the petrographic study. A Norelco fluorescence unit, equipped with air and vacuum paths, was fed with cellulose backed briquettes (the sample was finely ground, then reinforced with cellulose powder and pressed at 30,000 p.s.i. during one minute). A number of standards with contrasting compositions were used to calibrate the fluorescence unit (Table 3); the calibration curves are shown in Figs. 15 to 22. A detailed discussion of the characteristics of the curves and further information regarding the technical set-ups will be found in the Appendix. An analysed specimen was used as external standard, and peak and background readings for it were determined in sequence with three unknown samples. The reproducibility of the readings for the element analysed in the specimen gives an evaluation of the stability of the unit with time. The standard deviation calculated for the external standard permits evaluation of the limit of detectability of the element considered: this limit is taken here as three standard deviations above the mean background level, thus ensuring that, above this level, there is a quasi certitude that the energy detected corresponds to an actual content of the element analysed. Limits of detectability are given in Table 4. The stability values should not be taken as indices of the precision of the analyses which depends on both the stability of the unit and on the approximation made

TABLE 3

CHEMICAL COMPOSITIONS OF THE STANDARDS USED TO CALIBRATE THE
X-RAY UNIT

No. of Sample	R-58	R-59	1A	88	R-56	R-67	G I	W I	R-48
SiO ₂	4.39	2.04	14.12	0.31	74.77	54.26	72.48	52.55	41.90
TiO ₂	0.07	0.06	0.16	0.005	0.60	0.28	0.26	1.08	2.25
Al ₂ O ₃	1.07	0.62	4.16	0.067	10.27	5.55	14.20	14.98	15.77
Fe ₂ O ₃	0.62	0.62	1.63	0.084	3.30	1.51	1.86	11.08	14.22
MnO	0.02	0.02	0.038		0.02	0.01	0.025	0.161	0.25
MgO	2.51	14.86	2.19	21.48	1.54	1.96	0.37	6.59	1.49
CaO	45.7	34.8	41.32	30.49	1.26	16.98	1.35	10.98	9.70
K ₂ O	0.58	0.28	0.71	0.03	2.00	0.80	5.52	0.62	0.40
SrO			0.23				0.025	0.01	
Rb ₂ O							0.022	0.00	

Carbonates

R-58 and R-59 are samples of Mississippian carbonates from the Thornton Creek Section, Alberta. They were collected by Walasko (1962) during his work for the Geological Survey of Canada.

1 A and 88 are samples from the U.S. National Bureau of Standards, circular 552, second edition.

Shales

R-56 is a Wapiabi shale

R-67 is a Besa River shale

Igneous Rocks

G I and W I are the well known standards of the U.S. Geological Survey. R-48 is a melanite-ouachitite from the Rock Analysis Laboratory of the University of Alberta, Edmonton.

TABLE 4

<u>Constituent</u>	<u>Wt. in standard ppm</u>	<u>Std. Deviation ppm</u>	<u>Detectability ppm</u>
MgO	214,800	2,950	9,000
K ₂ O	5,800	18	54
Al ₂ O ₃	10,700	296	900
SiO ₂	20,400	620	1,800
CaO	304,900	67	200
TiO ₂	2,600	50.5	150
MnO	250	7	21
Fe ₂ O ₃	18,600	129	400
SrO	250	2	6
Rb ₂ O	220	5	15

when the X-ray energy is supposed to be related linearly to the content in the element analysed. This second factor is usually preponderant leading to a sizeable imprecision; in this study, precision was better than 15 percent, which was found sufficient for the writer's needs.

Ten elements were selected for analysis: calcium, magnesium, potassium, iron, aluminium, silica, titanium, manganese, rubidium and strontium. The choice was done in such a way as to represent all the major constituents of the dolomites as well as some important trace elements; the limits imposed by the fluorescence unit forbade the analysis of elements of atomic number smaller than twelve (magnesium), or of elements whose content was smaller than a few parts per million. Sulfur, generally a good indicator of the amount of pyrite, was not measured because of the importance of the anhydrite content, which would have voided the results of meaning.

Fifty-eight compound samples were taken from the three cores in such a way as to represent the various petrographic facies as well as possible. Seven additional samples were taken from places deemed of particular interest so that comparison with the compound samples could reveal possible compositional differences. Table 4 shows the precise location and the vertical range of the samples.

RESULTS

The results of the analytical work are shown in Figs. 9 to 14 and Tables 5 to 8. So that the chemical variations could be discussed in terms of the mineralogy, the contents in CaO , MgO , K_2O , SiO_2 , Al_2O_3 and Fe_2O_3 were recast to dolomite, calcite, magnesite, illite, quartz and hematite. Dolomite content was calculated on the basis of both CaO and MgO values, and the lower result was kept; surplus was considered to be calcite or magnesite according to

TABLE 5
LOCATIONS OF THE X-RAY SAMPLES

<u>Sample Number</u>	<u>Well</u>	<u>Location</u>	<u>Interval represented</u>
#21	Imperial Leduc 200	16-18-50 - 26 W 4	5088-5091
#22	"	"	5091-5095
#23	"	"	5095-5098
#24	"	"	5098-5103
#25	"	"	5103-5106
#26	"	"	5106-5109
#27	"	"	5109-5115
#28	"	"	5115-5116
#29	"	"	5116-5118
#30	"	"	5118-5120
#31	"	"	5120-5121.5
#32	"	"	5121.5-5123
#33	"	"	5123-5126
#34	"	"	5126-5128
#35	"	"	5128-5131
# 6	"	"	5131-5136
#36	"	"	5136-5141
#37	"	"	5141-5144
#38	"	"	5144-5147
#39	"	"	5147-5152
#40	"	"	5152-5156
#41	"	"	5156-5165
#42	"	"	5165-5178
#43	"	"	5178-5182

#44	Imperial Leduc 200	16-18-50 - 26 W4	5182-5186
#45	"	"	5186-5194
#46	"	"	5194-5202
#47	"	"	5202-5210
#48	Imperial Leduc 177	12-2-50 - 26 W 4	5073-5082
#49	"	"	5082-5089.5
#50	"	"	5089.5-5096
#51	"	"	5096-5100
#52	"	"	5100-5110
#53	"	"	5110-5115
#54	"	"	5115-5119
#55	"	"	5119-5130
#56	"	"	5130-5142
#57	"	"	5142-5158
#58	"	"	5158-5173
#59	"	"	5173-5186
#60	"	"	5186-5206
# 7	"	"	5206-5213
# 3	Futurity Weisener I	2-17-49 - 25 W 4	5140-5146
#61	"	"	5146-5149
#62	"	"	5149-5153
#63	"	"	5153-5157
#64	"	"	5157-5169
#65	"	"	5169-5178
#66	"	"	5178-5187
#67	"	"	5187-5199
#68	"	"	5199-5209

#69	Futurity Weisener I	2-17-49 - 25 W 4	5209-5214
#70	"	"	5214-5223
#71	"	"	5223-5233
#72	"	"	5233-5239
#73	"	"	5239-5251
#74	"	"	5251-5264
#75	"	"	5264-5276
#76	"	"	5276-5292
#11	Imperial Leduc 200	16-18-50 - 26 W 4	5202
#12	"	"	"
# 1	Futurity Weisener I	2-17-49 - 25 W 4	5246
# 2	"	"	5257.5
# 4	"	"	5223
# 5	"	"	5151

TABLE 6

RESULTS OF THE CHEMICAL ANALYSES

All values are in percent of total weight except for Rb₂O and SrO, which are in ppm

Sample Number	CaO %	MgO %	K ₂ O %	SiO ₂ %	Al ₂ O ₃	Fe ₂ O ₃ %	MnO %	TiO ₂ %	Rb ₂ O ppm	SrO ppm	Sr/Ca $\times 10^4$
#21	30.415	21.91	.081	.645	.186	.246	.019	.012		60.5	2.35
#22	30.27	22.185	.087	1.147	.186	.263	.014	.011		77	3.01
#23	30.395	17.72	.070	1.048	.176	.250	.014	.015		289	11.27
#24	30.30	21.91	.056	.837	.156	.228	.015	.008		45.5	1.78
#25	30.43	22.00	.044	.369	.090	.199	.016	.004		69.5	2.70
#26	27.14	19.885	.665	6.093	1.800	.744	.025	.086	20	90	3.92
#27	24.21	17.49	.633	16.051	1.488	.428	.010	.100	11	72	3.52
#28	30.22	21.495	.065	1.698	.302	.232	.019	.024		78	3.05
#29	30.55	22.185	.149	.645	.116	.171	.016	.008		73	2.83
#30	30.54	21.955	.043	.389	.121	.165	.018	.008		66	2.56
#21	30.495	21.265	.083	.620	.186	.290	.018	.021		64	2.48
#32	29.71	21.265	.214	1.981	.498	.452	.015	.027		79.5	3.17
#33	30.54	21.31	.029	.177	.050	.192	.013	.007		76	2.94
#34	29.86	21.54	.126	1.299	.241	.147	.014	.020		63.5	2.52
#35	30.55	21.68	.032	.162	.050	.169	.016	.003		81	3.14

Sample Number	CaO %	MgO %	K ₂ O %	SiO ₂ %	Al ₂ O ₃	Fe ₂ O ₃ %	MnO %	TiO ₂ %	Rb ₂ O ppm	SrO ppm	Sr/Ca x 10 ⁴
# 6	30.32	21.77	.045	.231	.126	.163	.011	.007		69	2.69
#36	30.575	20.71	.048	.300	.111	.161	.015	.010		82.5	3.19
#37	29.70	19.61	.044	.404	.151	.298	.017	.011		252	10.06
#38	30.03	21.955	.095	.541	.292	.401	.020	.014		187	7.37
#39	29.55	18.46	.061	.364	.146	.324	.014	.011		347	13.89
#40	30.55	21.17	.028	.133	.055	.198	.015	.007		79.5	3.08
#41	29.04	19.79	.333	1.885	.870	.460	.013	.049	06	120.5	4.91
#42	29.90	20.115	.048	.261	.111	.193	.014	.009		199	7.87
#43	29.94	20.76	.140	.827	.342	.316	.016	.016		107.5	4.25
#44	30.535	21.54	.116	.527	.211	.159	.011	.017		88.5	3.43
#43	30.63	21.265	.074	.384	.141	.191	.017	.012		85.5	3.30
#46	30.21	21.035	.089	.694	.226	.180	.017	.013		155.5	6.09
#47	30.035	20.115	.025	.157	.070	.225	.014	.002		277.5	10.93
#48	28.47	19.885	.375	4.110	.794	.614	.020	.054	32.5	71.5	2.97
#49	29.65	20.16	.130	2.254	.236	.210	.013	.021		301.5	12.03
#50	27.515	19.47	.464	6.891	.955	.496	.015	.069	10	73	3.14
#51	30.02	20.805	.065	1.102	.116	.326	.016	.010		150	5.91
#52	28.81	19.56	.222	3.125	.437	.288	.013	.031		301	12.36

Sample Number	CaO %	MgO %	K ₂ O %	SiO ₂ %	Al ₂ O ₃	Fe ₂ O ₃ %	MnO %	TiO ₂ %	Rb ₂ O ppm	SrO ppm	Sr/Ca $\times 10^4$
#53	30.23	21.54	.071	.896	.116	.142	.016	.010		464.5	18.18
#54	30.31	20.62	.092	.773	.151	.126	.016	.013		146	5.70
#55	30.255	19.975	.063	.359	.146	.207	.013	.005		233.5	9.13
#56	30.11	20.115	.040	.408	.116	.252	.016	.009		338	13.28
#57	30.46	21.45	.026	.143	.080	.194	.018	.006		224	8.70
#58	30.73	21.77	.040	.197	.075	.205	.017	.009		119	4.58
#59	30.73	20.94	.038	.325	.095	.194	.014	.004		372	14.32
#60	30.50	21.17	.067	.477	.095	.203	.012	.007		137.5	5.33
# 7	31.315	18.825	.551	4.243	1.398	.838	.017	.069	23.5	145.5	5.50
# 3	10.38	8.65	1.841	41.364	7.170	2.261	.022	.502	95	83.5	9.52
#61	13.04	9.67	1.037	45.237	3.117	1.106	.023	.202	26.5	60	5.44
#62	30.26	21.08	.071	.851	.111	.361	.018	.011		118	4.61
#63	29.60	20.39	.154	2.943	.261	.246	.021	.026		71.5	2.86
#64	29.775	20.85	.139	2.372	.261	.246	.014	.025		126	5.01
#65	25.72	17.77	.618	10.774	1.443	.556	.017	.109	13	82.5	3.80
#66	30.205	21.68	.081	.984	.141	.160	.013	.015		111	4.35
#67	23.175	17.535	.594	19.693	1.151	.453	.015	.156	59.5	225	11.49
#68	30.17	21.45	.130	1.176	.241	.165	.012	.018		112	4.39

Sample Number	CaO %	MgO %	K ₂ O %	SiO ₂ %	Al ₂ O ₃	Fe ₂ O ₃ %	MnO %	TiO ₂ %	Rb ₂ O ppm	SrO ppm	Sr/Ca $\times 10^4$
#69	30.33	21.13	.074	1.166	.136	.151	.015	.012	105	105	4.10
#70	30.30	20.805	.143	1.004	.271	.176	.016	.020	85	85	3.32
#71	30.56	21.45	.064	.418	.116	.123	.012	.008	129	129	4.99
#72	30.29	21.31	.052	.660	.111	.188	.013	.007	190.5	190.5	7.44
#73	30.47	22.23	.057	.591	.116	.113	.011	.008	111	111	4.31
#74	30.57	22.23	.065	.546	.101	.126	.012	.008	109	109	4.22
#75	29.68	21.035	.198	1.732	.377	.246	.012	.026	138	138	5.50
#76	29.78	21.495	.217	1.786	.473	.272	.013	.028	109	109	4.33
#11	25.445	.185	.002	.044	.005	.013	.001	.001	1573.5	1573.5	73.17
#12	30.54	22.14	.023	.138	.040	.103	.015	.005	87.5	87.5	3.39
# 1	27.03	18.78	.445	8.771	1.001	.340	.013	.085	53	53	2.75
# 2	29.83	20.16	.143	1.442	.362	.687	.011	.002	173.5	173.5	5.88
# 4	29.39	21.59	.139	3.667	.201	.104	.009	.002	78.5	78.5	3.16
# 5	30.40	21.265	.032	.340	.070	.255	.029	.003	497	497	19.39

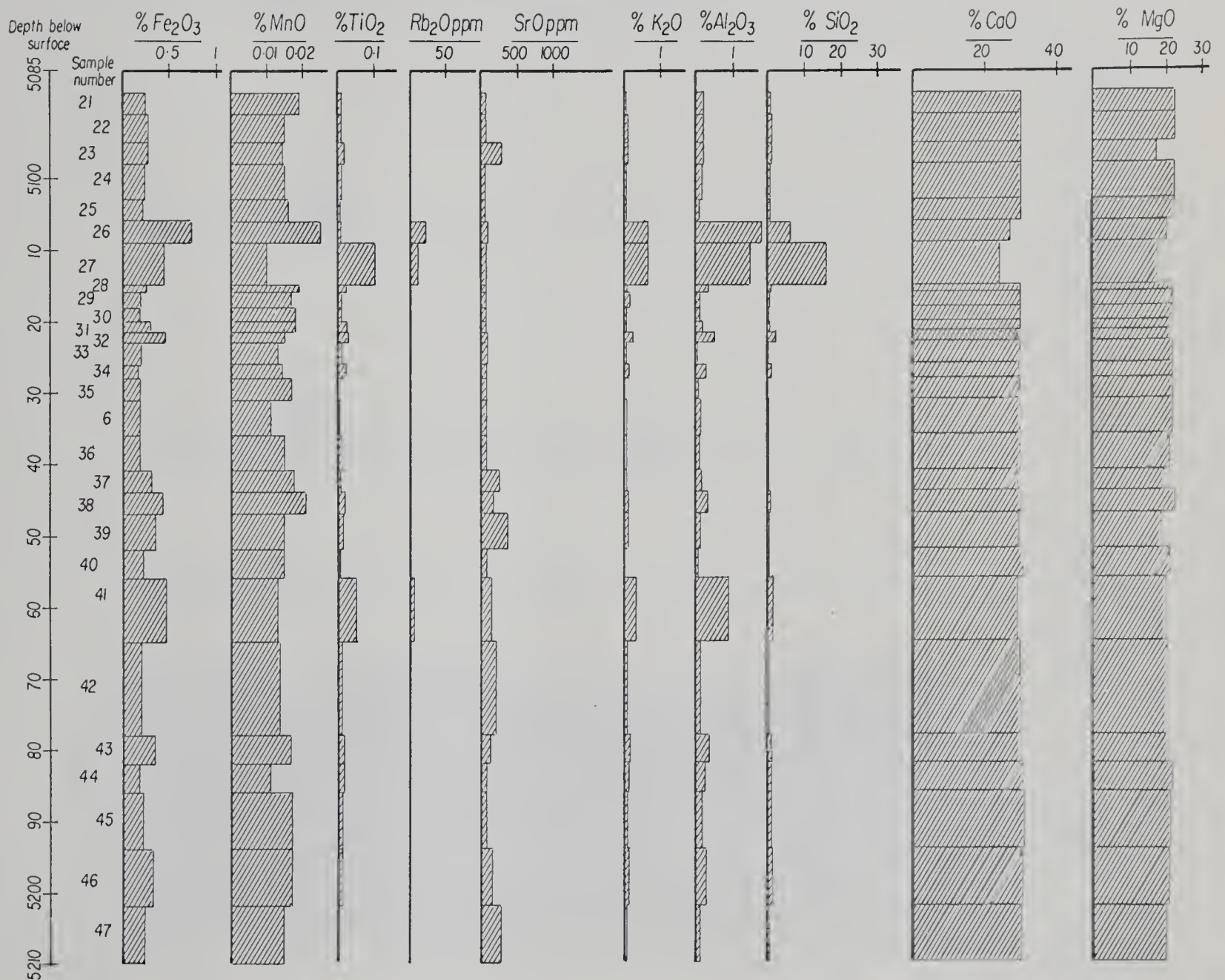
TABLE 7

RESULTS OF THE CHEMICAL ANALYSES RECAST TO MINERAL COMPOSITION

Sample Number	Calcite %	Dolomite %	MgCO ₃ %	Illite %	Quartz %	Hematite %	Total Minerals
#21		100.02	0.08	0.685	0.335	0.25	101.37
#22		99.54	0.88	0.735	0.815	0.26	102.23
#23	10.26	81.05		0.59	0.78	0.25	92.93
#24		99.64	0.255	0.47	0.62	0.23	101.215
#25		100.07	0.25	0.37	0.20	0.20	101.09
#26		89.26	0.77	5.625	3.55	0.745	99.95
#27		80.00		5.36	13.625	0.43	99.415
#28	0.585	98.32		0.55	1.45	0.23	101.135
#29		100.47	0.455	1.255	0.07	0.17	102.42
#30		100.42		0.35	0.225	0.165	101.17
#31	1.64	97.26		0.70	0.30	0.29	100.19
#32	0.24	97.26		1.81	1.16	0.45	100.92
#33	1.61	97.47		0.25	0.06	0.19	99.58
#34		98.20	0.15	1.065	0.82	0.15	100.385
#35	0.70	99.16		0.27	0.04	0.17	100.34
# 6	0.08	99.58		0.38	0.06	0.16	100.26
#36	2.795	94.74		0.405	0.12	0.16	98.22
#37	4.33	89.69		0.37	0.235	0.30	94.655
#38		98.76	0.75	0.805	0.18	0.40	100.895
#39	6.93	84.42		0.52	0.13	0.325	92.325
#40	1.97	96.84		0.24	0.02	0.20	99.27
#41	2.70	90.53		2.815	0.61	0.46	97.115
#42	3.43	92.00		0.405	0.08	0.19	95.105

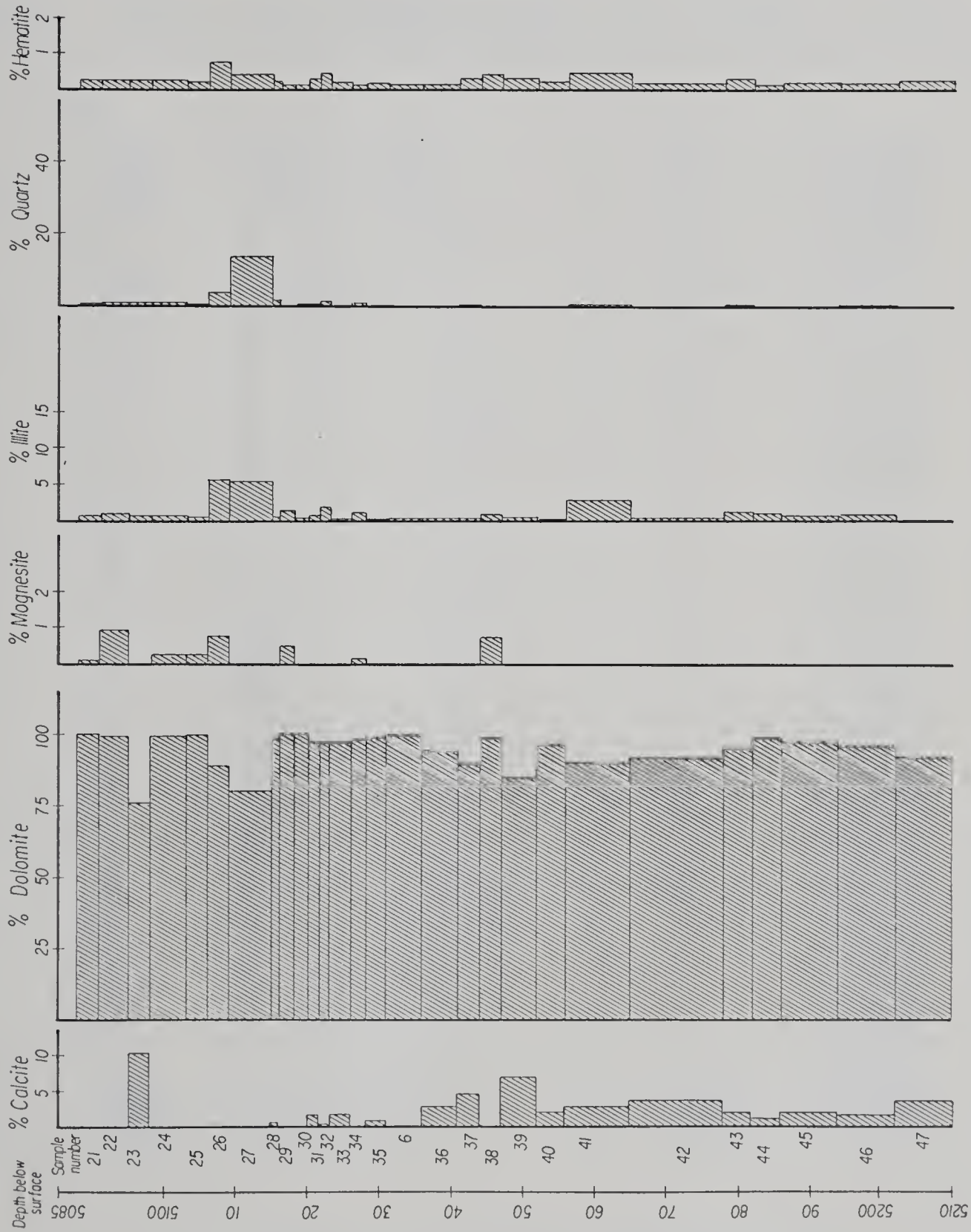
Sample Number	Calcite %	Dolomite %	MgCO ₃ %	Illite %	Quartz %	Hematite %	Total Minerals
#43	1.905	94.95		1.185	0.29	0.315	98.645
#44	1.025	98.53		0.98	0.08	0.16	100.775
#45	1.88	97.26		0.625	0.10	0.19	100.055
#46	1.70	96.21		0.75	0.35	0.18	99.19
#47	3.67	92.00		0.21	0.06	0.225	96.055
#48	1.45	90.95		3.17	2.675	0.615	98.86
#49	2.875	92.21		1.10	1.76	0.21	98.155
#50	0.78	89.05		3.925	5.115	0.50	99.37
#51	1.93	95.16		0.55	0.85	0.325	98.815
#52	2.87	89.47		1.88	2.275	0.29	96.785
#53	0.475	98.53		0.60	0.085	0.14	99.83
#54	2.91	94.315		0.78	0.42	0.125	98.55
#55	4.41	91.37		0.53	0.12	0.21	96.64
#56	3.81	92.00		0.34	0.25	0.25	96.65
#57	1.12	98.11		0.22	0.04	0.195	99.685
#58	0.80	99.58		0.34	0.04	0.205	100.965
#59	2.86	95.79		0.325	0.18	0.195	99.35
#60	1.87	96.84		0.57	0.22	0.20	99.70
# 7	9.16	86.10		4.66	2.135	0.84	102.895
# 3		34.12	2.495	15.57	34.32	2.26	88.765
#61		42.87	0.61	8.775	42.265	1.105	95.625
#62	1.68	96.42		0.60	0.58	0.36	99.64
#63	2.21	93.26		1.30	2.355	0.245	99.37
#64	1.38	95.37		1.18	1.84	0.245	100.015
#65	1.80	81.26		5.225	8.41	0.555	97.25

Sample Number	Calcite %	Dolomite %	MgCO ₃ %	Illite %	Quartz %	Hematite %	Total Minerals
#66	0.09	99.16		0.685	0.675	0.16	100.77
#67		76.21	1.825	5.02	17.42	0.45	100.925
#68	0.60	98.11		1.10	0.68	0.165	100.655
#69	1.69	96.63		0.625	0.88	0.15	99.975
#70	2.43	95.16		1.21	0.46	0.175	99.435
#71	1.29	98.11		0.54	0.175	0.12	100.235
#72	1.17	97.47		0.44	0.46	0.19	99.73
#73		100.20	0.67	0.485	0.37	0.11	101.835
#74		100.54	0.52	0.55	0.295	0.125	102.03
#75	0.755	96.21		1.68	0.97	0.245	99.86
#76		97.93	0.17	1.83	0.96	0.27	101.16
#11							
#12		100.44	0.37	0.195	0.05	0.10	101.155
# 1	1.625	85.89		3.76	7.07	0.34	98.685
# 2	3.20	92.21		1.21	0.895	0.69	98.205
# 4		96.65	0.94	1.175	3.135	0.10	102.01
# 5	1.47	97.26		0.27	0.22	0.265	99.485



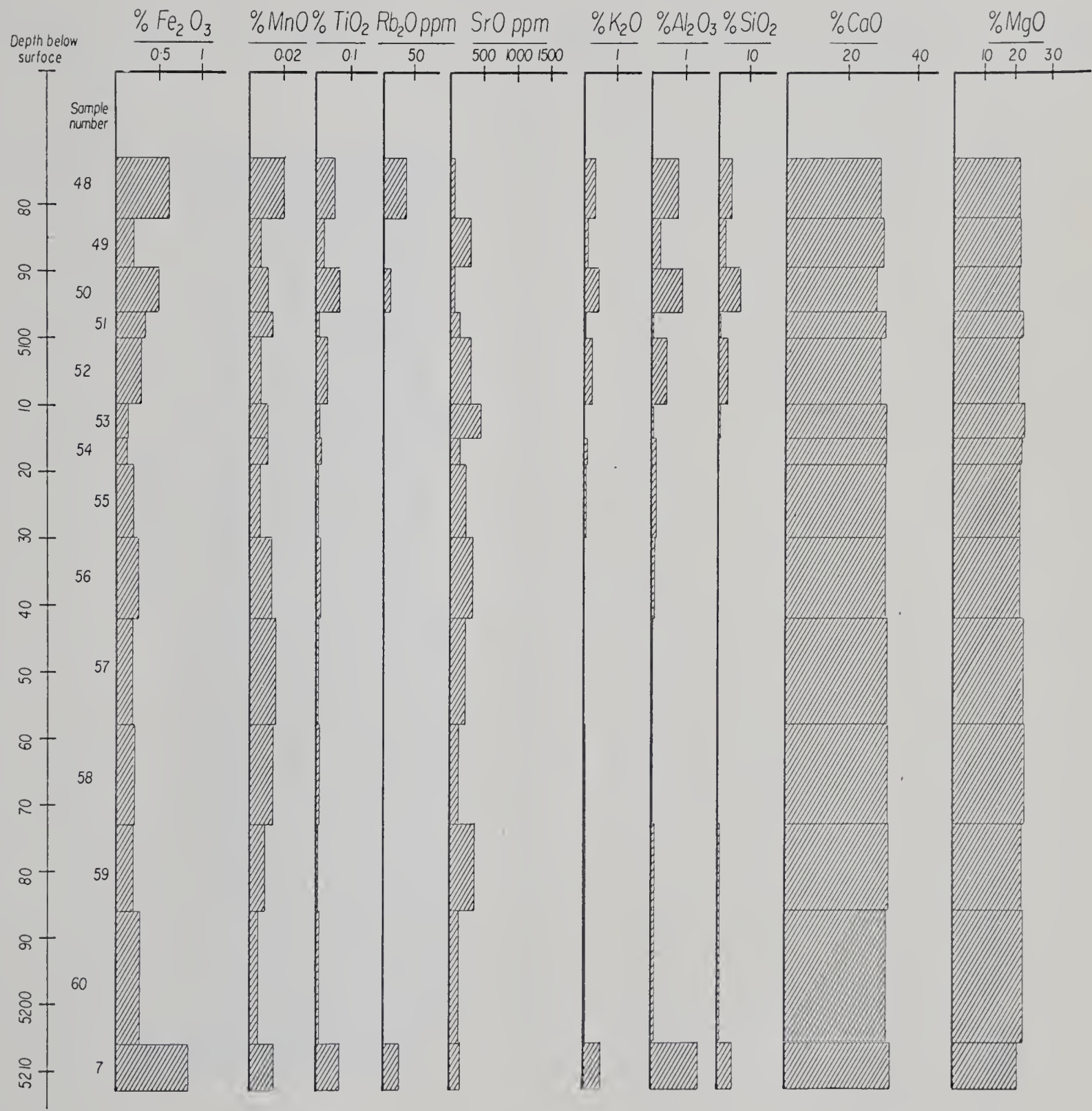
CHEMICAL COMPOSITION OF THE ROCKS IN THE
NISKU FORMATION, IMPERIAL LEDUC 200WELL

Figure 9.



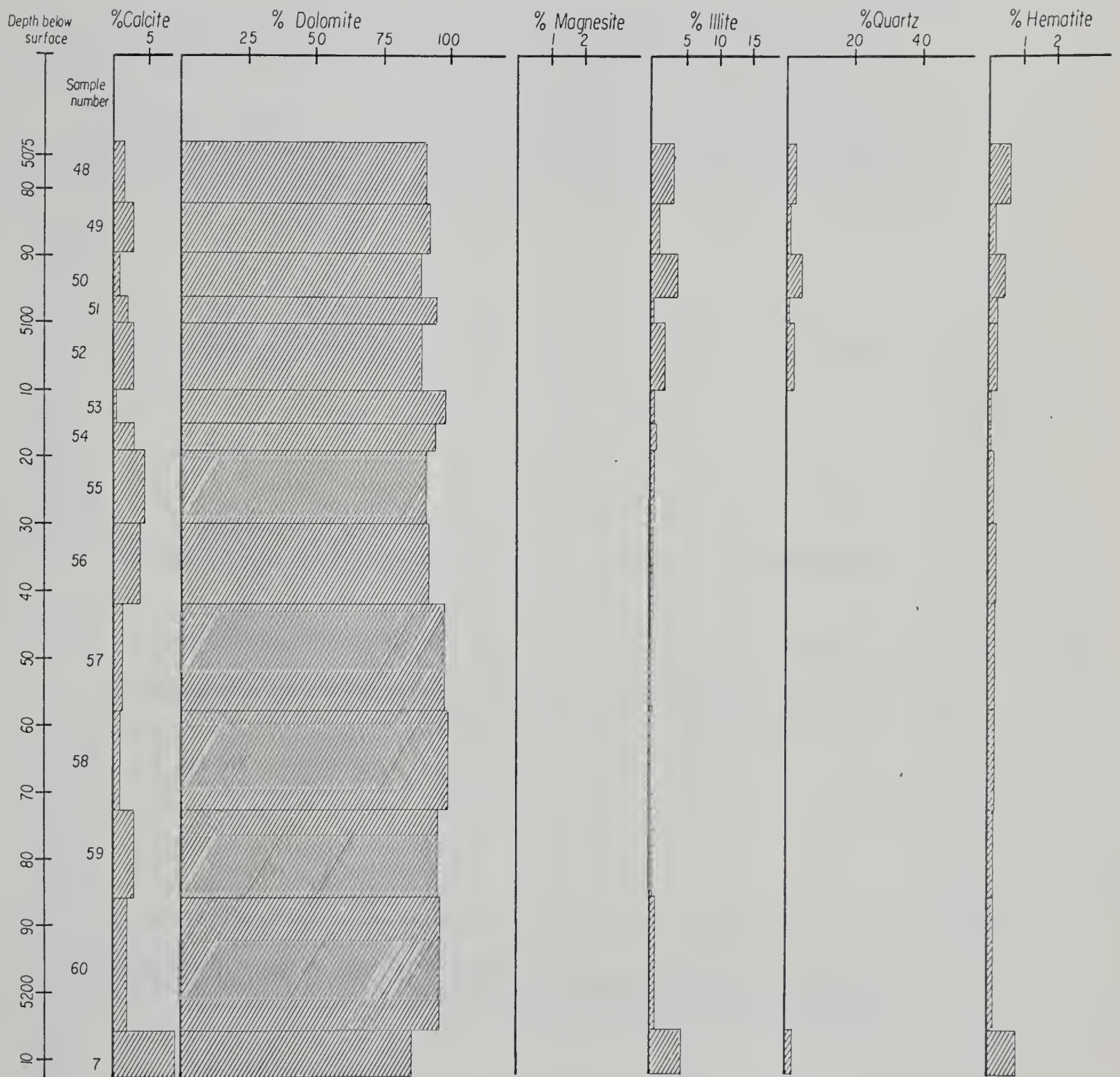
*CALCULATED MINERAL COMPOSITION OF THE ROCKS IN THE
NISKU FORMATION, IMPERIAL LEDUC 200WELL*

Figure 10.



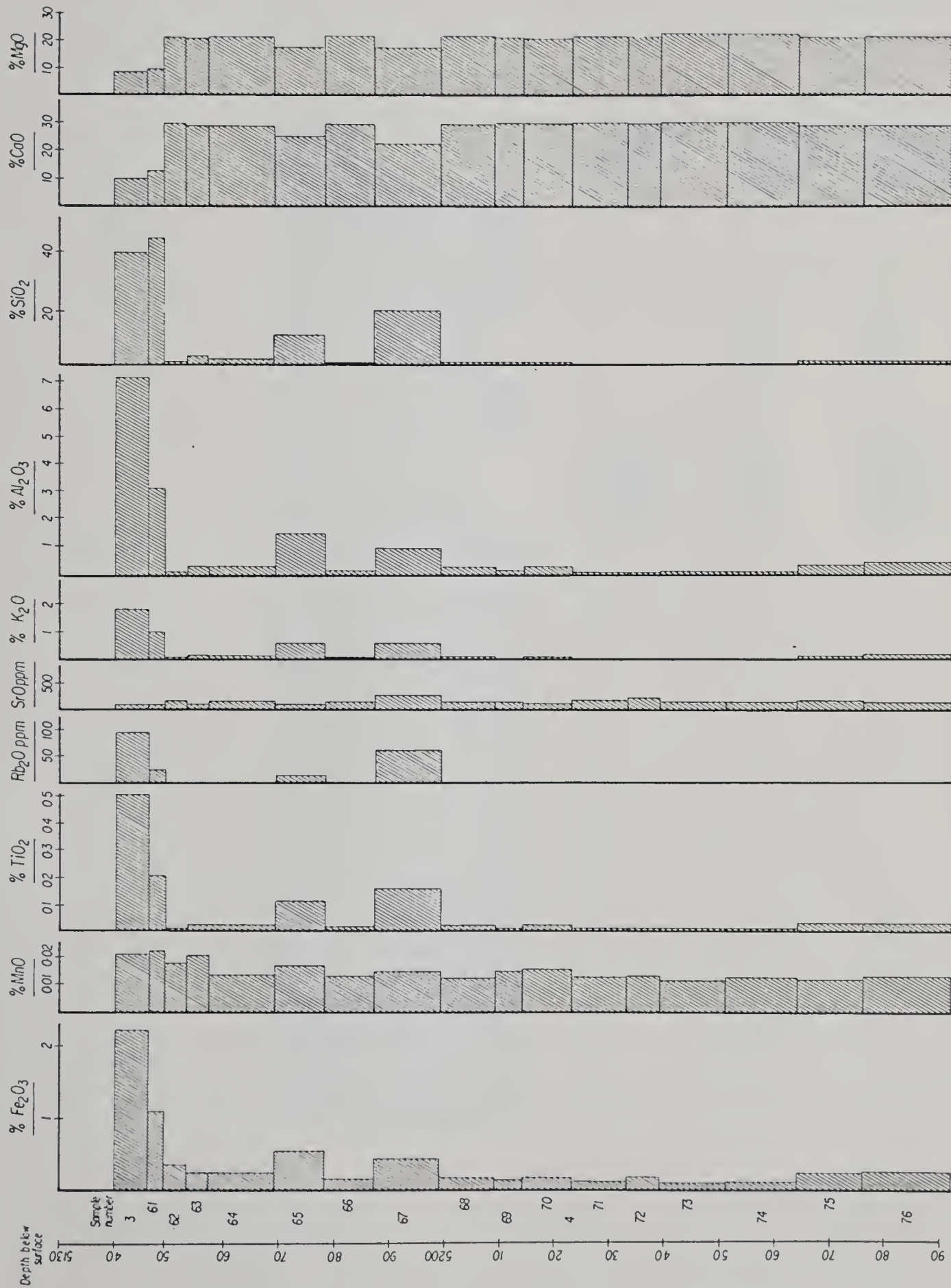
CHEMICAL COMPOSITION OF THE ROCKS IN THE
NISKU FORMATION, IMPERIAL LEDUC 177 WELL

Figure 11.



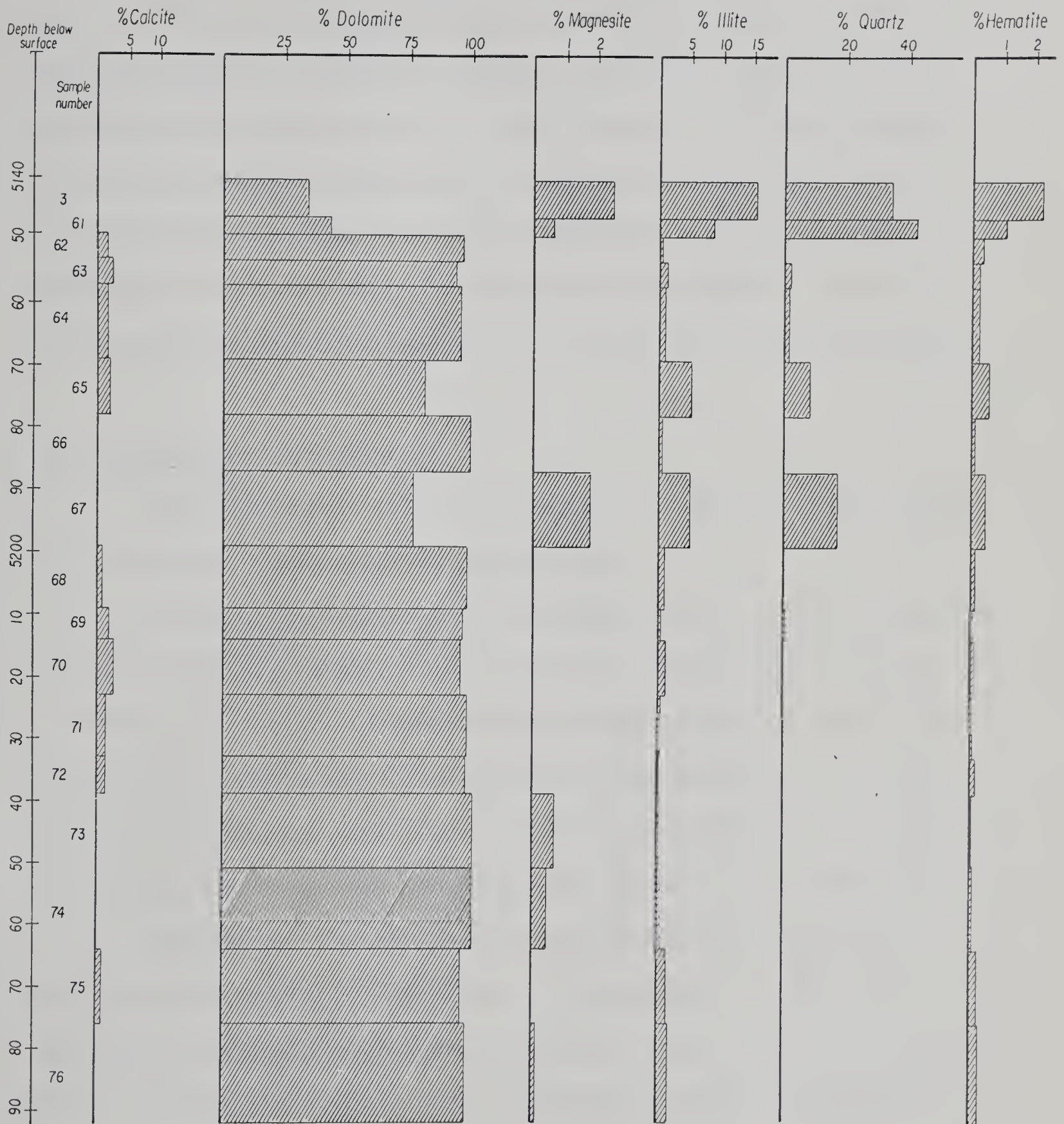
CALCULATED MINERAL COMPOSITION OF THE ROCKS IN THE
NISKU FORMATION, IMPERIAL LEDUC 177 WELL

Figure 12.



CHEMICAL COMPOSITION OF THE ROCKS IN THE
NISKU FORMATION, FUTURITY WEISENER I WELL

Figure 13.



CALCULATED MINERAL COMPOSITION OF THE ROCKS IN THE
NISKU FORMATION, FUTURITY WEISENER 1 WELL

Figure 14.

what value was retained. Illite is the only clay mineral that could be detected by X-ray diffraction methods; as its exact composition could not be determined, the formula used here is that of stoichiometric muscovite. Quartz values were obtained by subtracting from the SiO_2 results the quantity of silica contained in the illite. Hematite corresponds to the Fe_2O_3 values; although it is well known that large quantities of iron can be substituted for magnesium in the dolomite lattice (Graf, 1960), it was impossible to calculate the amount of diadochically substituted iron separately from that in other mineralogical forms.

Distribution of the major elements

The stoichiometric calcium and magnesium contents for a pure dolomite are: 30.41 percent CaO and 21.86 percent MgO.

Calcium: The CaO content is remarkably uniform in all the petrographic facies except the argillaceous dolomite or facies 5. The average for the non argillaceous samples is 30.16 percent CaO, and their variational range extends from 28.47 to 31.32 percent. The argillaceous dolomite samples have a much wider variational range, from 10.26 to 27.52 percent, and are as a rule poorer in calcium than the others. This reflects a higher content in detrital material.

Magnesium: The behaviour of magnesium follows closely that of calcium, because of the Mg/Ca atomic ratio, very near 1/1 in almost pure dolomites. Non-argillaceous dolomites have an average content of 21.05 percent MgO, and range from 19.56 percent to 22.23 percent MgO. Argillaceous samples range from 8.65 percent to 18.78 percent MgO.

Carbonate minerals: No definite visual relationship between the recast mineralogical content and the petrographic facies, except the argillaceous dolomite, could be established. It is possible that a statistical treatment of the data would show otherwise, but time was not sufficient to envisage a study of this

kind. Calcite contents vary between 0 and 10.26 percent, dolomite contents between 34.12 and 100.54 percent, magnesite contents between 0 and 2.495 percent. Carbonate contents are much lower in the argillaceous dolomite than in the other facies. One interesting anomaly shows up in a few samples: Nos. 23, 39, 3, 61, of which sample 23 is a good instance. Its dolomite content, calculated from the MgO figure, is only 81.05 percent leading to a total of 92.93 percent. Sample 39 shows the same kind of discrepancy, while samples 3 and 61, with totals also abnormally low, had their dolomite content computed from the CaO figures. According to the writer, these discrepancies are best explained by the intervention of a differential leaching process, which would wash out preferentially the calcium or the magnesium atoms in the dolomite lattice. The method used for the computation of dolomite would then ignore a certain amount of excessive CO_3 -- groupings, giving therefore an abnormally low total. The computation of the dolomite content is made, as already indicated, from the calcium or magnesium content, the lowest result being retained. This system has the advantage of giving a minimum dolomite content, but it does not take into account the possibility of vacant atomic positions in the dolomite lattice. Therefore, the surplus calcite or magnesite obtained from the dolomite result corresponds to an actual surplus only when such vacant positions do not exist. Furthermore, the terms calcite or magnesite do not imply that the elements are under crystalline carbonate form; they are just simple ways of expressing a departure from the pure dolomite composition.

The section in the Imperial Leduc 200 well shows a good overall balance between surplus calcite and surplus magnesite. There, the magnesite is concentrated in the upper Nisku while the calcite is found mostly in the middle and the lower Nisku; this indicates a good correlation between the magnesite content and the amount of terrigenous material.

The Imperial Leduc 177 well shows no magnesite at all, which correlates

with a lesser amount of quartz silt. This is somewhat surprising, for it is known that the "shore line" was nearer this well than from Imperial Leduc 200. However, it reinforces the trend already noted in Imperial Leduc 200.

The Futurity Weisener I well has a surplus of both calcite and magnesite, the latter limited to the argillaceous dolomite facies and facies (4b) and (4c), whereas the former is evenly distributed through the rest of the section. There, too, the magnesite is associated with quartz silt and illite, indicating more land-bound conditions. The highest surpluses of magnesite as well as the highest detrital contents are found in this well.

On the whole, there is a definite relationship between the amount of detrital material and the amount of surplus magnesite. It is thought that a greater influence of the land, bringing shallower and warmer waters, greater concentrations in seawater, pH changes, and a higher magnesium content in calcareous organisms (Chave, 1952), was more favourable to the fixation of magnesium by the calcitic sediments, leading to complete dolomitization and excess fixation of magnesium.

A special notice was taken of sample 7, which shows a decrease in dolomite content correlative with an increase in calcite content; the behaviour of this sample with respect to the other elements analysed indicates, according to the writer, that sample 7 belongs to the uppermost Ireton.

Detrital material: Included under this heading are K_2O , SiO_2 , and Al_2O_3 , and the corresponding minerals, illite and quartz. They are grouped here together because of their similar behaviours, dictated by their common terrigenous origin.

The argillaceous dolomite is sharply characterised chemically and mineralogically by detrital contents much above those of the other facies.

The average detrital contents for non-argillaceous dolomites are seen in Table 8. Among these rocks, facies (4a) and (4c) which look slightly argillaceous in the hand specimens show illite contents up to two or three times as high as the

average, and are separable from the rest. The other facies could not be distinguished. It is possible that the use of sophisticated statistical methods would impart greater confidence in the significance of small differences.

Minor elements

Iron: The behaviour of iron in the three wells analysed follows very closely that of illite. It is logical that the iron, contained in sediments as ferric hydroxide mostly, would be comprised in the hydrolizate fraction. The iron substituted for magnesium is probably an unimportant fraction of the total iron content, for it is known that ferroan dolomites are generally of hydrothermal origin. Even if all the iron was substituted to magnesium in the crystal lattice, a calculation based on the average iron content of the non-argillaceous dolomites, 0.214 percent Fe_2O_3 , shows that the proportion of substituted atoms would still be less than 1.6 percent. The importance of pyrite is deemed negligible, according to visual estimates of its abundance. However, it is possible that the greater content of pyrite in argillaceous dolomite slightly reinforces the above mentioned behaviour.

Manganese: The average value of MnO is 0.0155 percent; its variational range is 0.009 to 0.029 percent and no obvious trend is observed. However, the writer is confident that a definite relationship binds the variations of manganese and iron; this should be confirmed by a statistical test of dependance which time did not permit making.

Titanium: The behaviour of titanium is sympathetic to those of illite, and iron, because of titanium's concentration in the hydrolizate fraction. There is a striking similarity between the histograms of titanium and illite, to the point that even small amounts of argillaceous dolomite amidst a mainly non-argillaceous sample are enough to give a powerful "kick" on the histogram of TiO_2 . The average amount of TiO_2 in non-argillaceous samples is 0.011 percent. Its variational range

is from 0.002 to 0.028 percent. The slightly argillaceous facies such as (4a) and (4c) are richer than the average, but relatively high contents of TiO_2 (0.020 percent for instance) can be found in seemingly non-argillaceous facies: especially so in the upper Nisku, where illite is relatively abundant.

Trace elements

Rubidium: Only ten rubidium readings were obtained. Locus of rubidium is essentially illite, a fact certainly due to the diadochical replacement of potassium by rubidium which is by far the most common mode of occurrence of rubidium in nature.

Strontium: The average strontium content of the Nisku rocks is 150 ppm. In the Imperial Leduc 177 and 200 wells, the variations of the strontium content follow closely those of the calcite, which suggests strongly the concentration of the strontium in the calcite; this is supported by the fact that nine samples of pure dolomite with no excess calcite and no important argillaceous material ranged from 45.5 to 187 ppm, averaging 93.5 ppm. This last value is not very different from the one determined by Campbell and Lerbekmo (1965) in pure Paleozoic dolomite (70 ppm), but contrasts strongly with the general average of the Nisku rocks. In the Futurity Weisener I well, the relation is complicated and generally masked by the preferential concentration of the strontium in the clay minerals of the abundant argillaceous dolomite.

Anhydrite, as was expected, shows contents of strontium much greater (up to ten times as great) than those of dolomite.

Results from specially selected samples

A sample of white anhydrite (No. 11), collected from the lower Nisku of the Imperial Leduc 200 well, was compared with the ones analyzed by Murray

(1964). Like Murray's replacement samples, it has a rather high magnesium content, but it does not exhibit high aluminium or silica content. This is probably the result of a mixed pore filling and replacement origin.

Sample 2, representing late-stage dolomite, is much richer in iron and aluminium than the compound sample representing the encompassing interval. The contents of the other elements analysed were comparable. Unfortunately, only one sample of late-stage dolomite was analysed, which does not permit generalization of the observation; however, the writer thinks that this discrepancy is significant, and should permit the chemical distinction between first and late-stage dolomite. The excess iron and aluminium do not correspond to a higher argillaceous content, for potassium and silica contents are comparable to those in the reference sample; it is possible that the magnesium bearing solutions contained some amount of iron and aluminium, probably as colloids, and that these elements were incorporated in the rock during the late dolomitization. This process would have been somewhat similar to that of lateritization, by which elements such as carbonates and silica are dissolved and washed away while the alumina and the ferric hydroxide remain.

Sample 5, a dolomitized calcarenite, is markedly poorer than the reference sample in iron, titanium, potassium, aluminium, silica; it has comparable calcium and magnesium contents and is markedly richer in manganese and strontium. These trends clearly indicate an open marine source for the sand-sized material. The calcarenite, located at the top of the upper Nisku in the Futurity Weisener I well, is probably composed of material stemming from an open marine environment and washed by the currents toward the shores.

DISCUSSION OF THE RESULTS

The results of the chemical work are in good accord with the present literature. The argillaceous dolomite facies is easily singled out by its high

detrital content, leading to values of K_2O , SiO_2 and Al_2O_3 that are many times higher than the corresponding averages values for the non-argillaceous material. In addition to this, the argillaceous dolomite facies has abnormally high contents of titanium, iron, and rubidium. Weber (1964b) had noticed the concentration of these elements in the more argillaceous dolomites which is readily explained by simple mineralogical and geochemical observations.

The slightly argillaceous facies such as (4a) and (4c) show the above mentioned trends at a lesser degree.

The other petrographic facies do not have chemical particularities that would permit their delimitation from a chemical profile alone, although slight variations in the chemical contents may be correlated with different facies. It is possible that a better analytical treatment of the data could lead to a finer appreciation, therefore permitting the establishment of chemical facies. However, the writer doubts that relationships not evident on the various chemical and mineralogical histograms could have a high level of significance.

The chemical profiles drawn for each well show some striking similarities, especially in the upper Nisku. This has permitted correlation of the three sections. Furthermore, the argillaceous bottom of the core in Imperial Leduc 177 was judged to be indicative of the uppermost Ireton because of its high argillaceous content, leading to remarkable increases in the K_2O , Al_2O_3 , SiO_2 , Rb_2O , TiO_2 , MnO values, and because of its abnormally high content of calcite. The top of the core in the Futurity Weisener I well was considered to be lowermost Calmar because of its proportion of silt and of illite, much higher than for any other sample in the three cores.

A comparison between the values recorded in this study and the ones published by Weber (1964b) confirm chemically that the Nisku dolomites are secondary. Potassium content in the Nisku is notably lower than the average of

the secondary dolomites, (3970 ppm) but is still within the range of variations. Aluminium contents in the Nisku are much more similar to those of secondary dolomites than those of primary dolomites. The same is true for iron. Manganese and titanium are notably lower than Weber's values for either primary or secondary dolomites. Strontium values are similar to Weber's.

TABLE 8

AVERAGE CHEMICAL COMPOSITION OF THE NISKU DOLOMITES

CaO	(non argillaceous, non silty dolomites)	.....	30.16%
MgO	" "	.....	21.05%
K ₂ O	" "	.....	0.063%
SiO ₂	" "	.....	0.466%
Al ₂ O ₃	" "	.....	0.131%
Fe ₂ O ₃	" "	.....	0.214%
MnO	(all dolomites)	.....	0.0155%
TiO ₂	(non argillaceous, non silty dolomites)	.....	0.011%
SrO	(all dolomites)	.....	150 ppm
Sr/Ca x 10 ⁴	(all dolomites)	.....	5.92

SUMMARY AND CONCLUSIONS

The study of three sections of the Nisku Formation of the Upper Devonian of central Alberta was undertaken to reconstruct the depositional environments, collect data on the paleoecology and test the influence of the petrographic variations on the chemical composition.

Lower Nisku deposition was rather shallow, relatively quiet and muddy. middle and upper Nisku sedimentation was still shallower, effected in more turbulent waters. The upper Nisku is characterized by an increase in quartz silt content, already announcing the overlying Calmar Formation which was deposited in extremely shallow, quiet conditions, where a preponderantly terrigenous sedimentation took place.

The Imperial Leduc 200 and 177 sections, situated above a reefal development of the Leduc Formation, exhibit very similar features. The section in the Futurity Weisener I well, situated off reef to the east as regards the underlying Leduc, is markedly richer than the two others in detrital material and shows some indications of more turbulent depositional conditions. It may have corresponded to a shallow basin sheltered from the open sea by a topographic high formed by Nisku sedimentation above the Leduc reef.

Amphipora, a dendroid stromatoporoid, proliferated in the middle and upper Nisku environments, while the quieter lower Nisku was more favourable to the development of tabular stromatoporoids; encrusting "blue-green type" algae developed around the Amphipora stems.

The chemical study singled out the rock types with a relatively high detrital content, composed of illite and of quartz silt. Non-argillaceous facies could not be characterized by their chemical properties except when the source of the sedimentary material, because of different depositional conditions, had a

trace element content markedly different from that of the usual rocks of the Nisku Formation (for instance, sample 5).

The dolomitization of the Nisku took place in two successive phases. The first phase consisted of a volume for volume transformation, which affected the sedimentary features to various degrees, generally preserving the gross texture. This first dolomitization probably took place before the end of Wabamun time. In a second stage, highly saline magnesium-bearing solutions altered the rock around the fissures; this transformation completely obliterated the primary features and was associated with an enrichment in iron and aluminium.

Anhydrite, which may constitute up to 15 percent of the rock in some places, is the result of void filling and of replacement. Its presence may have helped the late-stage dolomitization.

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APPENDIX

FLUORESCENCE ANALYSIS

Sample Preparation

The samples obtained for the X-ray fluorescence analysis and the X-ray diffraction work were drilled out of the cores with a small diamond drill. This method prevented possible iron contamination in a crusher. The compound samples, representing 10 feet in the average, were obtained by continuous drilling along the core; the resulting powder was homogenized in a Pica Blender.

All samples were briquetted in an Applied Research Laboratories Inc. Briquetting machine Type 4451, for one minute, at a pressure of 30,000 p.s.i. The samples were backed and rimmed with cellulose powder for strength, the sample powder being cone-shaped. The diameter of the exposed sample was a little less than one inch because of the cellulose rim.

X-ray fluorescence

The briquettes were analyzed with Norelco X-ray fluorescence equipment, the basic unit (type 122 15/0) having a constant potential output. Radiation sources were W and Mo target tubes, energized by 50 kV and 40 mA, and a Cr target tube energized by 50 kV and 30 mA.

A.D.P., E.D.D.T. and LiF analysing crystals were used in combination with a scintillation counter and a flow proportional counter; the flow proportional counter was alimented with 0.25 S.C.F./hour supply of a 90 percent Methane, 10 percent Argon gas mixture. When necessary, an X-ray path in a 0.5 mm Hg vacuum was established. Pulse height Analysis was used for the light elements, and counts per ten seconds were used throughout, except for titanium which necessitated counting periods of twenty seconds. Complete recording conditions for individual

TABLE 9

Element	Peak	Background	Xtal	Ctr	-E	L	P. H. A. W		Path	Tube
Al	112.75	111.80	EDDT	F. P.	1640	12.5	14	Dif	Vac	Cr
Si	78.12	77.30	EDDT	F. P.	1605	11	9	Dif	Vac	Cr
Mg	106.47	105.50	ADP	F. P.	1630	10	12	Dif	Vac	Cr
K	20.25	19.00	EDDT	F. P.	1605	17.5	20	Dif	Vac	W
Ca	14.67	14.00	EDDT	F. P.	1610	2.5	17.5	Dif	Vac	W
Mn	62.93	61.60	LIF	F. P.	1600	8	-	Int	Air	Mo
Ti	86.14	85.20	LIF	F. P.	1580	19.5	13	Dif	Air	Mo
Fe	57.46	56.00	LIF	F. P.	1560	1.5	-	Int	Air	Mo
Rb	26.54	26.00	LIF	Scint	820	1.5	-	Int	Air	Mo
Sr	25.08	24.40	LIF	Scint	890	1.5	-	Int	Air	Mo

Peak and Background are measured in degrees 2θ .

Xtal is the analyzing crystal

Ctr indicates the type of counter employed : flow proportional or scintillation.

- E is the counter voltage.

P. H. A. is the pulse height analysis, mentioning the cut off level L, the width of the pulse W and whether the analysis was differential or integral.

The X-ray path was either in Air or in Vacuum.

EDDT : Ethylene - Diamine - Ditetra - Acetate

ADP : Ammonium Dihydrogen Phosphate

LIF : Lithium Fluoride

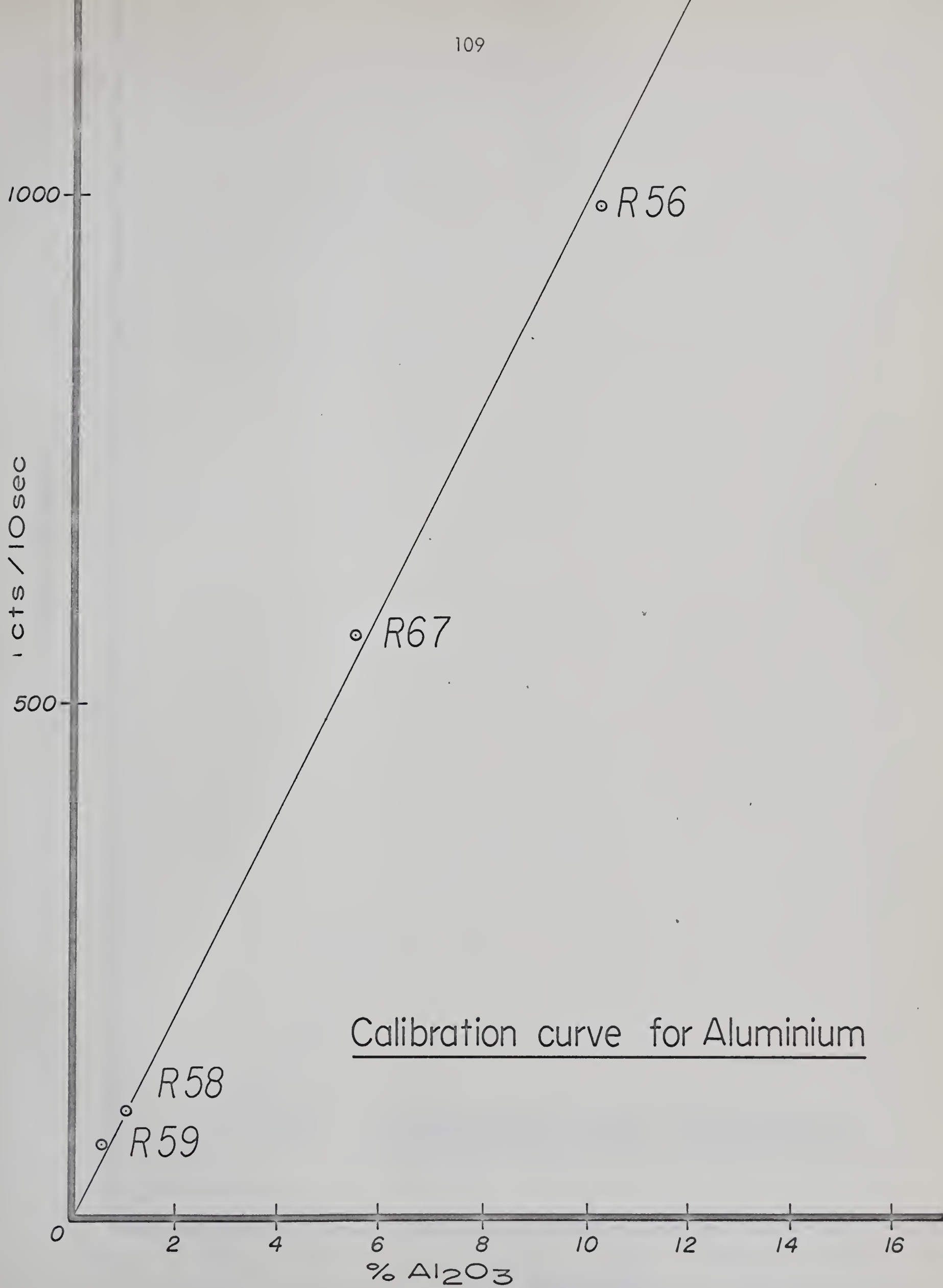


Figure 15.

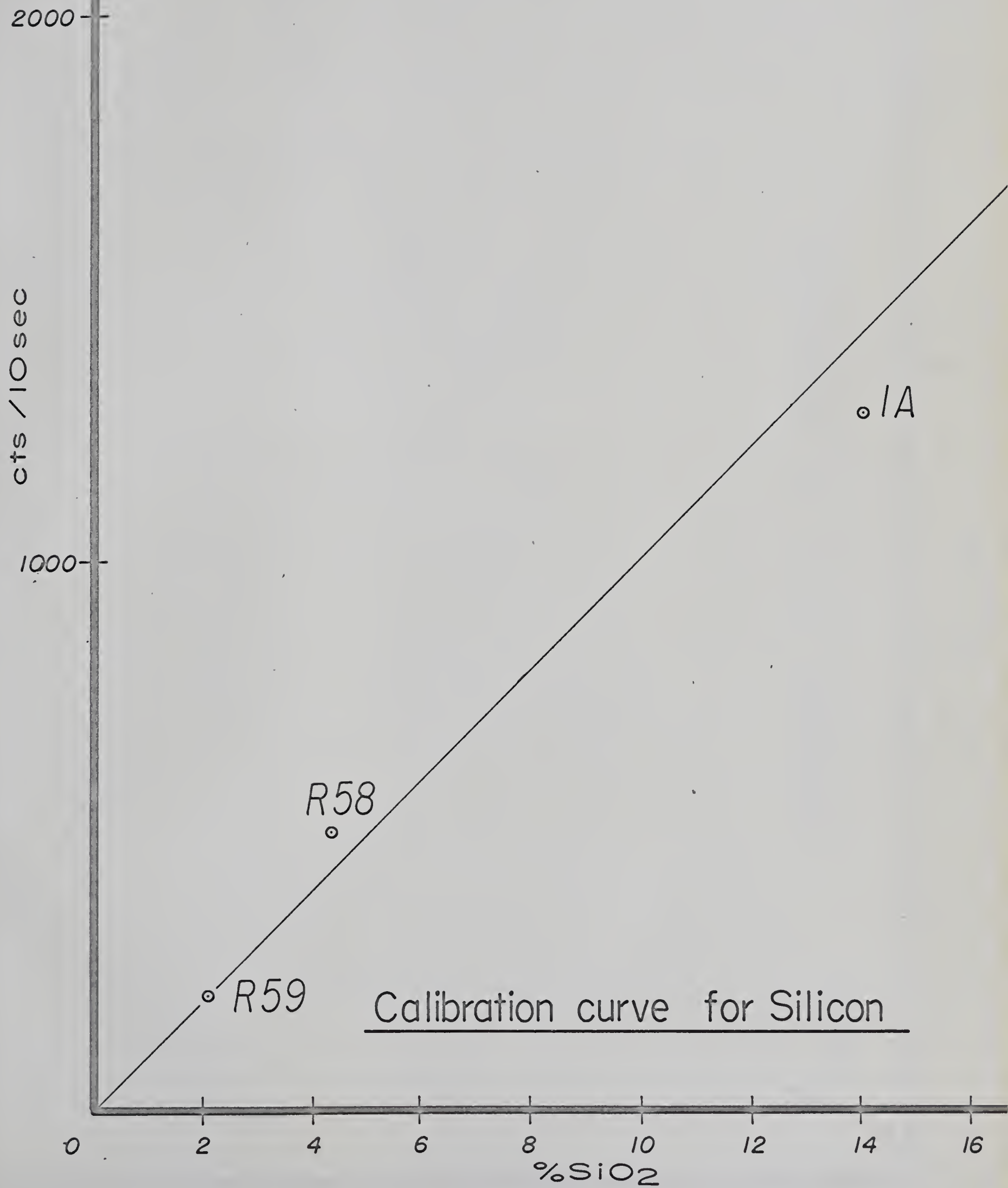
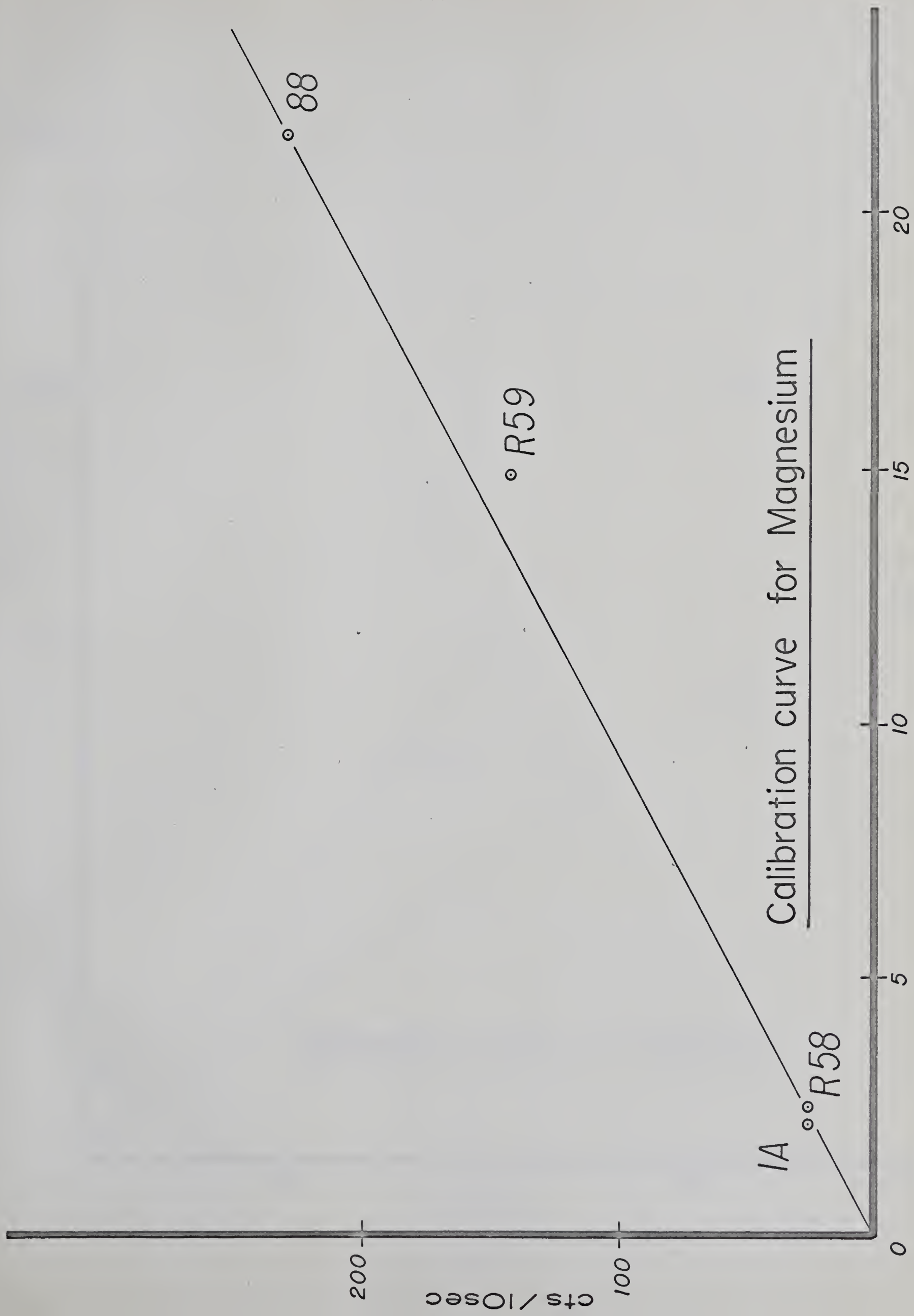


Figure 16.



Calibration curve for Magnesium

% MgO

Figure 17.

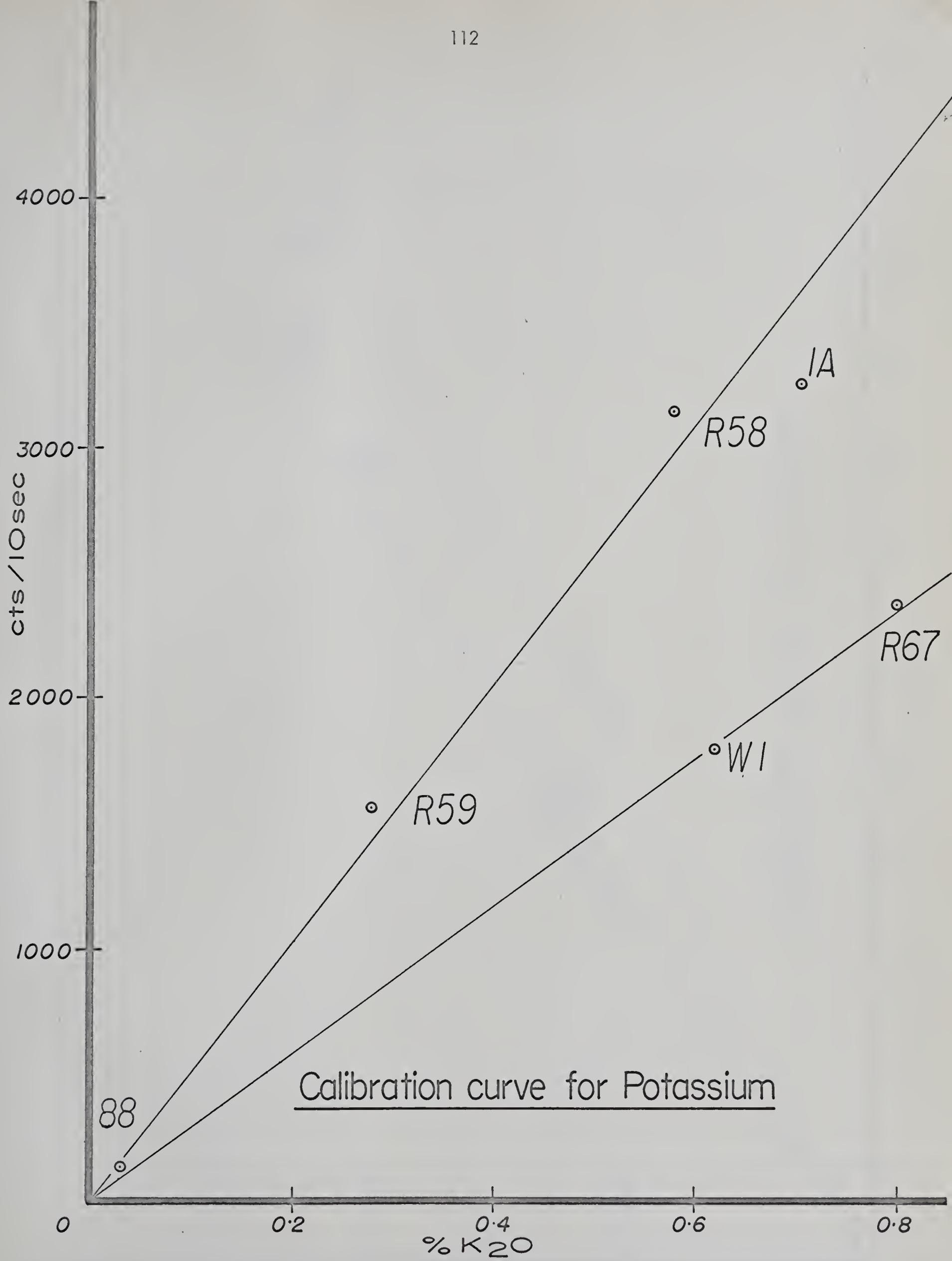
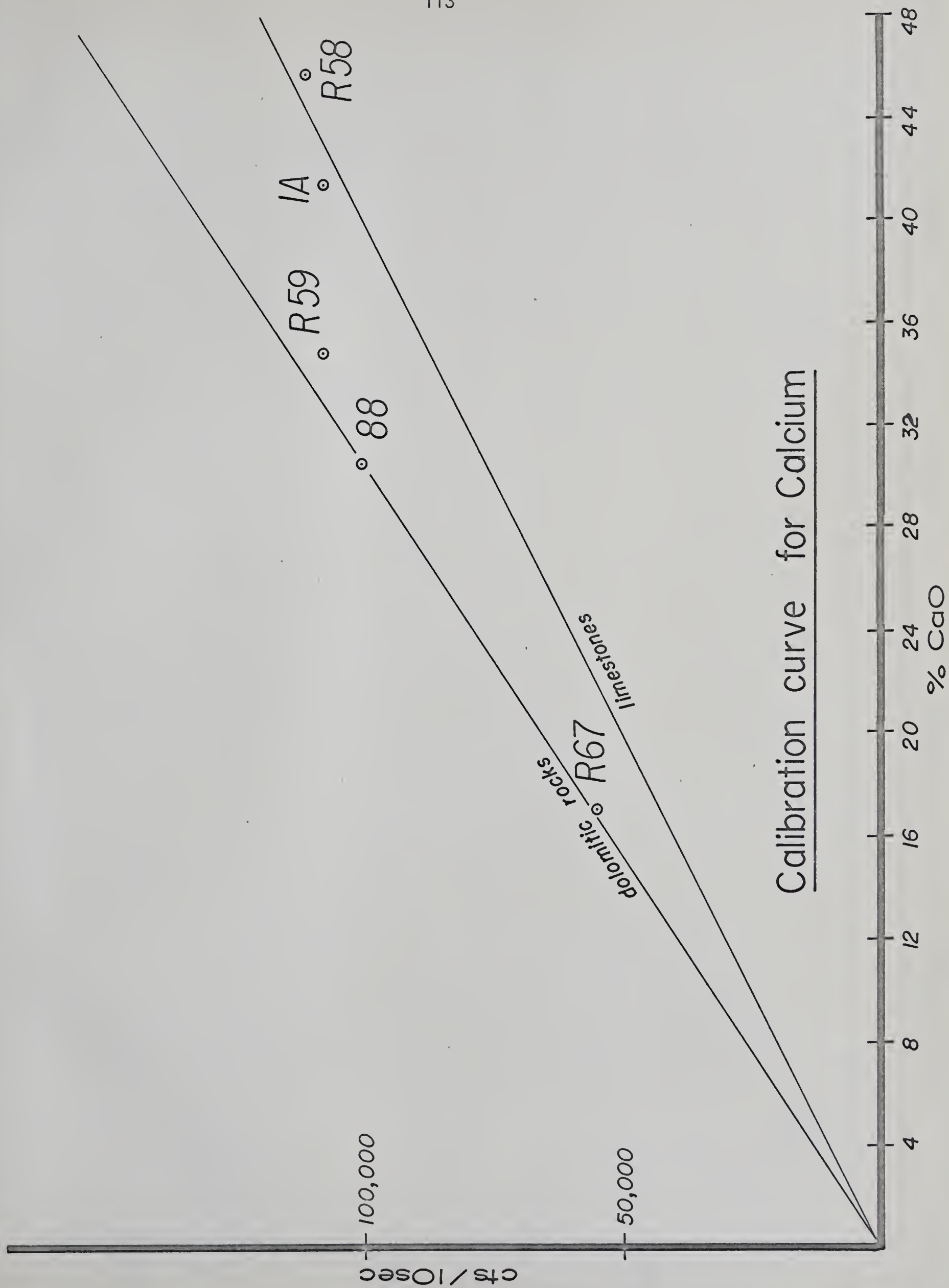
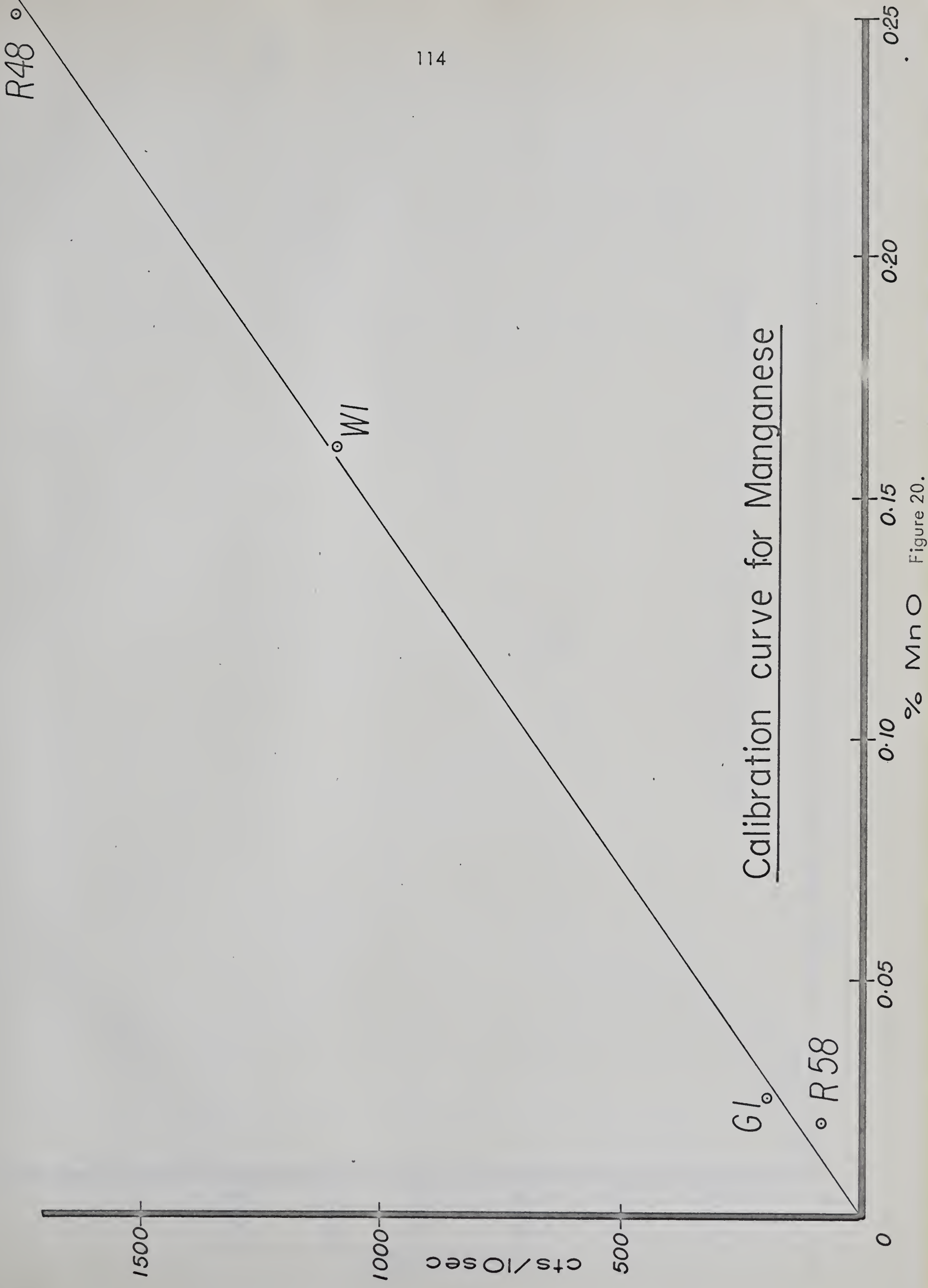


Figure 18.



Calibration curve for Calcium



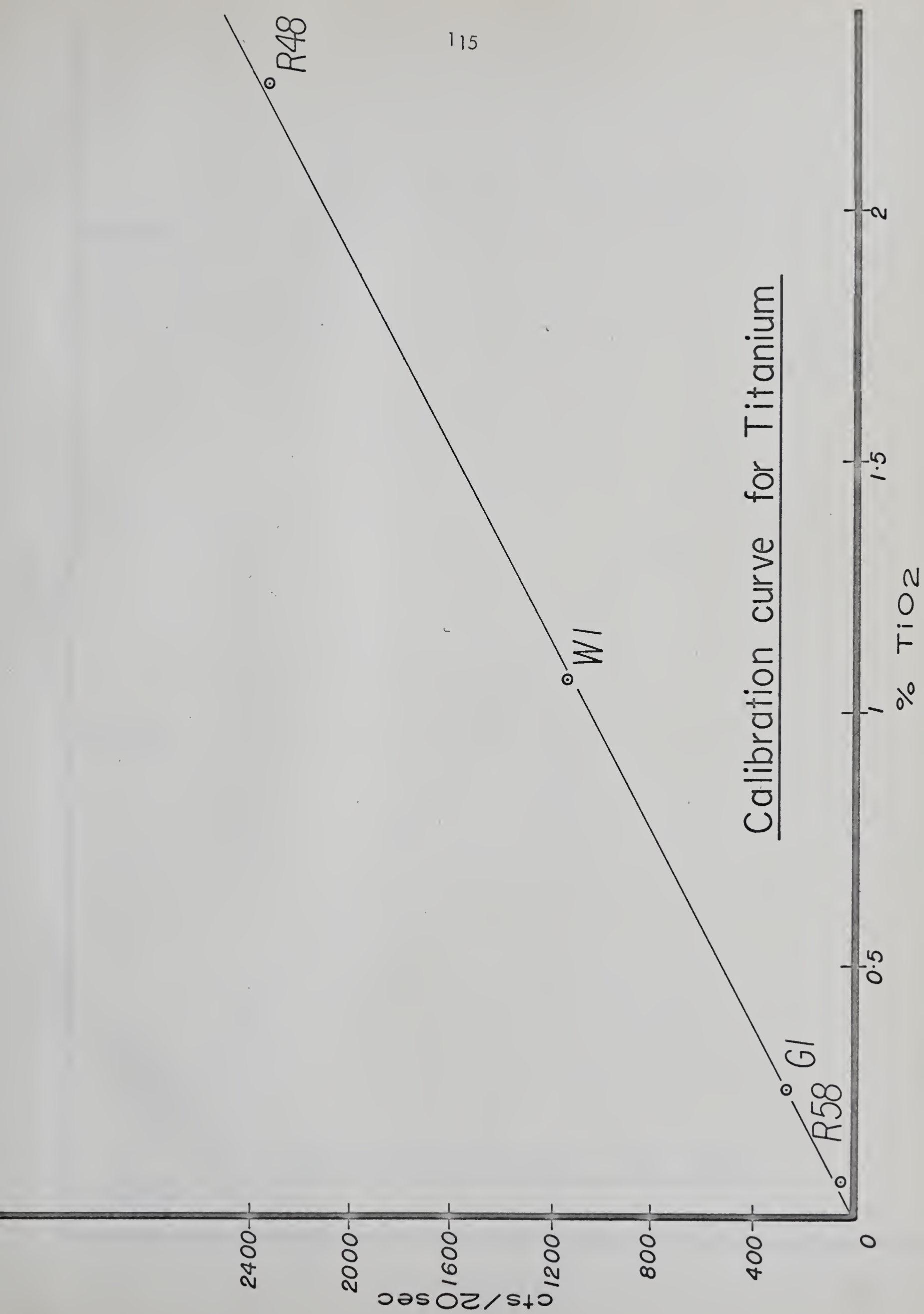


Figure 21.

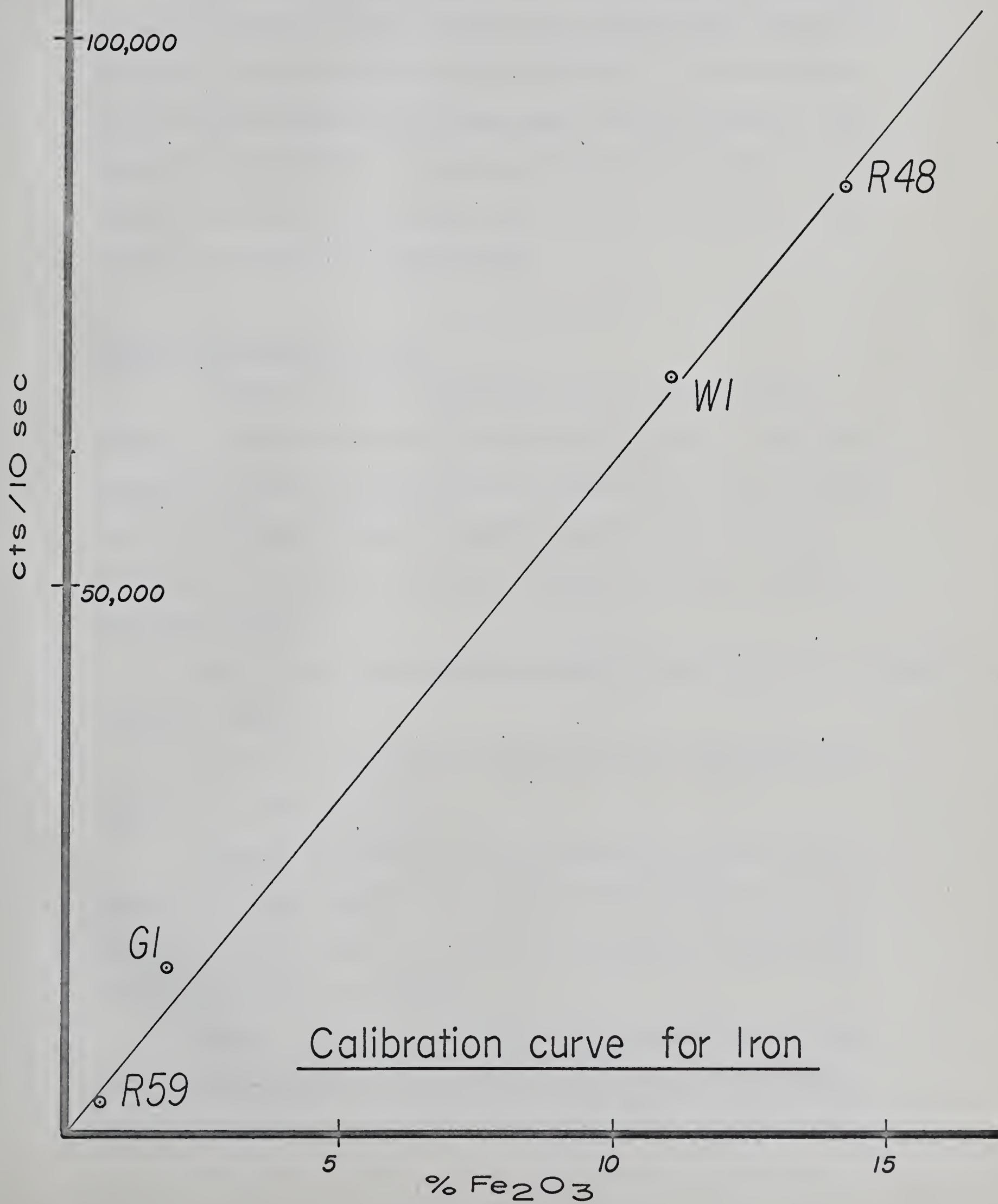


Figure 22.

elements are given in Table 7.

The conversion of counts per second to weight percent was made with conventional calibration curves determined with standards of known chemical composition for all elements with the exception of Rb and Sr. In the latter cases, the conversion was made using the Compton peak correction, according to the method of Reynolds (1963). This correction allows for the variations of the mass absorption coefficients of the samples, which is the most critical factor in the quantitative determination of trace elements.

Analysis of the calibration curves

Aluminium: The four analysed standards, two carbonates and two shales, in a counts-per-second versus percent-of- Al_2O_3 diagram, approximate a straight line, the deviation being less than 1.5 percent of the value indicated by the linear relationship for samples containing more than 1 percent Al_2O_3 . In the following lines, the degree of adjustment of the plots to a linear relationship will be called "precision".

Silica: Three carbonate samples plot along a straight line, with a "precision" better than 7 percent.

Magnesium: Four carbonate samples plot along a straight line with a "precision" better than 11 percent.

Potassium: The scattergram of four carbonate rocks, one shale and one igneous rock can be interpreted as the combination of two distinct linear relationships, one of which is valid for carbonates. The "precision" in regard to this straight line is better than 12 percent.

Calcium: Here too, the scatter of points representing four carbonates and one shale is interpreted as two distinct straight lines, one representing the dolomitic, the other representing the non-dolomitic rocks. "Precision" for the

dolomitic rocks is better than 7 percent.

Manganese: One carbonate and three igneous rocks plot along a straight line with a "precision" better than 1 percent for the high Mn contents. At low contents, a deviation as large as 42 percent can be observed.

Titanium: One carbonate and three igneous rocks plot along a straight line with a "precision" better than 2 percent, except for very low contents where a deviation of 50 percent is observed.

Iron: One carbonate and three igneous rocks plot along a straight line with a "precision" better than 1.5 percent, except for low contents where a deviation of 40 percent is observed.

It shall be noted that "precision", at low contents, is generally much poorer than at the more normal higher ones. It seems that the deviation from the straight line is somewhat independent of the amount in the sample of the element analysed; therefore the "Imprecision" at low contents can reach 50 percent.

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